Aging Effects on the Mechanical Properties of Waste Landfills

Nguyen Lan Chau

ABSTRACT

This is a geotechnical and environmental research about the aging effects on the mechanical properties of waste in landfills. The objectives of this dissertation are (1) to study the aging effects on the mechanical properties of waste mixture in coastal landfills, and (2) to evaluate the effects of waste biodegradation on the mechanical properties of municipal solid waste.

Coastal landfill sites not only offer an option for disposal but they also create a new land space after the completion of landfilling in Japan. To perform proper design against settlement, stability, and/or bearing capacity at landfill sites, the investigation of the geotechnical properties of the waste mixture layer, such as deformation and shear strength, is required. Therefore, this research focuses on the mechanical properties of waste mixture layer such as municipal solid waste incinerator ash, slag, soil, etc., in order to provide useful information on geotechnical properties to utilize coastal landfill sites after their closure. The effects of aging on the mechanical properties of waste mixture in coastal landfill sites were examined. A series of triaxial consolidated undrained compression tests (CU) and hydraulic conductivity tests were carried out on waste mixture samples before and after being cured in water that simulated water in coastal landfill sites for different periods to understand the change of mechanical properties of waste mixture. The results showed that an increase in the shear strength of the waste mixture samples with curing time was not due to bonding effect or other effect to improve the strength properties of solid phase but only due to the densification of the waste mixture sample. In addition, scanning electron microscope results and X-ray diffraction analysis on the waste mixture samples confirmed that ettringite and hydration products were formed reducing the volume of void space which in turn increased the shear strength and reduced the hydraulic conductivity of waste mixture samples.

In the second stage, a large-scale triaxial test was subjected to waste mixture samples due to the presence of large particles in coastal landfill sites. The value of shear strength parameters obtained from the triaxial tests for large samples are similar with those of small samples. However, the peak deviator stress for large samples was lower than those of small samples. This is due to the dissipation of pore water pressure that affects stress paths reducing in the strength of large samples. The smaller values of shear strength for large samples are also related to the crushability of large particle size. In the case of undrained condition and rapid loading in coastal landfill sites, it is suggested to use the large triaxial test.

In the next stage, the aging effect on the mechanical properties of waste in bioreactor landfills was investigated. Lab-scale bioreactor landfills were constructed to simulate municipal solid waste (MSW) landfills under anaerobic conditions. Synthetic MSW (SMSW) was prepared using different types of materials to create an approximate representation of a typical MSW sample in Vietnam. During the test, pH; chemical oxygen demand (COD) of the leachate and gas production were measured periodically for estimating the current biodegradation phase. Then, SMSW was extracted and tested for physical characteristics, settlement and shear strength properties. Consolidation test and consolidated undrained (CU) triaxial compression tests were conducted for initial waste and biodegraded waste. The consolidation test showed that compression index of MSW is reduced due to decreased of organic content with biodegradation process that increased in the dry density of MSW samples. From the triaxial test results, cohesion ranged from 4.4 to 10.1 kPa and friction angle varied from 20.8° to 41.2°. The cohesion was reduced with the biodegradation and this increased the concerns for the stability of bioreactor landfills. The changes in the geotechnical properties of the MSW due to waste degradation should be accounted in the analysis settlement and stability of bioreactor landfills.

ACKNOWLEDGEMENTS

This study was possible thanks to the Vietnamese government scholarship through the Ministry of Education and Training of Vietnam. The author is very grateful to the Ministry of Education and Training of Vietnam for the support and great opportunity of studying in Japan.

The author would like to expresses deep and sincere gratitude to his supervisor and main advisor of this research, Dr. Takeshi Katsumi, Professor of the Graduate School of Global Environmental Studies at Kyoto University, for his patience, motivation, enthusiasm, constructive suggestions as well as his inestimable supports throughout this work.

The author would also like to extend his gratitude to Dr. Toru Inui, Associate Professor of the Graduate School of Global Environmental Studies at Kyoto University, for his creative advice, kind cooperation, support and encouragement in this research.

The author expresses his gratitude to Dr. Mamoru Mimura, Professor of the Graduate School of Engineering, Kyoto University, for his valuable suggestion and comments on the contents of this dissertation.

Special acknowledgment is also due to Professor Koichi Ono, Professor Emeritus of Kyoto University, for his guidance, advice and encouragement.

The author gratefully thanks to Takai-sensei, Assistant Professor of the Graduate School of Global Environmental Studies at Kyoto University, for his invaluable support in the laboratory tests and research work.

Special thanks to Dr. Hermelinda Plata, for her help in paper preparation and writing this thesis as well as constructive comments and suggestions about this research.

The author also is grateful to Dr. Giancarlo Flores, for his comments and suggestion in this thesis.

Special thanks go to Yasumoto-san, the laboratory Assistant, Environmental Infrastructure Engineering Laboratory at Kyoto University, for all her help and support; to his former laboratory partner, Ikeda-san, for his hard work and assistance in conducting triaxial test ; to his former lab mates, Dr Li, Dr Abedin, Mari-chan, Kodama-san, Tua-san, Suwa-san, Giang-san, Haru-chan, Goto-san and his current lab mates, Naka-san, Tang-san, Harris, Uddin-san, Wang-san, Bobea-san, Mae-san, Mogami-san, Sano-san, Yano-san, Morita-san, Kihara-san, Oshima-san, Sumoto-san, Shotaro-san, Tamura-san, Kaori-san, Kihara-san, Kimura-san, for continuous support in academic field as well as in Japanese culture during the author's three years stay in Japan.

Thanks to all his Vietnamese friends, Viet Anh, Hung, Ngoc Hoa, Dien, Tung, Giang, etc., for supporting and sharing the most beautiful moments of life in Kyoto.

Last but not least, the author wishes to thank his family: his parents; his parents in law; his two younger brothers; his loving wife, Quynh Anh, for her support and encouragement during the three years living together in Japan; and specially to his daughter, a lovely angel, Giang Chau (Kaki-chan), who has given him the motivation to accomplish this achievement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 General Remarks

Municipal solid waste (MSW) management is becoming a worldwide challenge due to the rapid urbanization and growth in population that is accelerating its generation rate (Seo et al. 2004). MSW is the type of waste that includes primarily household waste (e.g. paper, plastic, package wrappings, food scraps, grass clippings, etc.). The MSW constituents can be divided into organic and inorganic (See Table 1.1).

Table 1.1 MSW composition for different income levels (Tchobanoglous et al., 1993)

Waste component	Countries income		
	High	**Medium**	**Low**
Organic			
Food Waste	6-30	20-65	40-85
Paper/Cardboard	20-45	8-30	1-10
Plastics	2-8	2-6	1-5
Textile	2-6	2-10	1-5
Rubber & leather	0-2	1-4	1-5
Wood & yard waste	10-20	1-10	1-5
Misc organic waste	<1	<1	<1
Inorganic			
Glass	4-12	1-10	1-10
Tin cans	2-8	1-5	1-5
Aluminium	0-1	1	1-3
Other metals	1-4	1	1-5
Dirt, ash etc.	0-10	1-30	1-40

Depending on the waste composition, there are various methods to treat the waste including reuse and recycling, composting, incineration, and disposal at landfill (Williams, 1998). Table 1.2 shows a comparison of waste treatment options for different countries. In this table, landfilling is the main option for solid waste disposal because landfilling is the cheapest and easiest way to dispose of waste. However, this kind of disposal method presents problems associated with lack of land to locate landfill sites as well as air and water pollution. Thus, it is essential to propose and apply new methods as waste management solutions.

Table 1.2 Comparison of waste treatment practices (%) (ADB 2011)

Country (Year)	**Untreated**	**Sanitary Landfill**	**Composting[a] and Recycling**	**Incineration**
Bangladesh (2001)	88	10	2	0
China (2006)	48	43	2	8
European Union[b]	0	45	36	19
Hong Kong	0	55	45	0
India (2001)	60	15	10	5
Japan (2005)	0	8	19	73
Nepal (2001)	70	10	5	0
Singapore (2007)	0	10	0	90
United States (2007)	0	54	34	13

[a]For Bangladesh, India, Nepal, and Sri Lanka, the figures reflect only composting activities. Recycling in these countries is done by the informal sector, and it is found that around 15%–20% of total waste, in India for example, could be recycled.
[b] Average of 15 European Union countries.
Sources: ADB. 2005. Country reports for Bangladesh, India, Nepal, and Sri Lanka. Unpublished documents under RETA 6337: Development Partnership Program for South Asia; ADB and United Nations Economic and Social Commission for Asia and the Pacific. 2000. *State of the Environment in Asia and the Pacific 2000*. New York: United Nations; and Zhu, D., et al. 2008. *Improving Municipal Solid Waste Management in India: A Sourcebook for Policy Makers and Practitioners*. Washington, DC: World Bank.

Recently, bioreactor landfills have attracted attention as an option for waste treatment. In a bioreactor landfill, MSW decomposition and stabilization is accelerated by re-circulating the generated leachate, which creates a more favorable environment for the biological decomposition of organic matter inside the landfill. Some of the advantages of bioreactor landfills include: 1) increase effective refuse density and landfill capacity; 2) increase rate of gas production and 3) reduce the cost of landfill maintenance after closure (Barlaz and Reinhart 2004).

Nowadays, in Japan, it is difficult to construct inland waste disposal sites due to limited available land. Incineration has become a solution to reduce waste volume with up to 78% of Japan's waste being incinerated (Shimaoka et al. 2007). Thus, coastal landfilling has become an important disposal method of municipal solid waste incinerator ash (MSWIA), and recently, many studies have been focused in the geotechnical properties of MSWIA to reclaim landfill sites after its closure and to reuse landfilled sites land space. Normally, the types of waste accepted into coastal landfill site include MSWIA, industrial waste, surplus soil and dredged material. Therefore, it is important to understand the geotechnical properties of waste mixture in coastal landfill site.

This study focused on the aging effects on the mechanical properties of waste. There are different aspects related to aging effects such as the creep behavior, the biodegradation and hydration process of material. Aging effects is defined as the time-dependent changes in the stress-strain properties, including all the mechanical properties of geomaterials which could be described as a function of time (Tatsuoka et al. 2008). For aging effects presented by Tatsuoka et al. (2008), the authors focused on the rate-dependent response of material due to viscous property such as creep and stress relation, etc. It has been reported that the aging effect on sand increases its strength and stiffness (Mitchell and Solymar 1984; Schmertmann 1991; Baxter and Mitchell 2004; Mitchell 2005). There are various mechanisms that can explain the aging effects in soil; however, the dominant factors are mechanical and/or chemical.

The aging effects of MSW material can be considered not only creep behavior similar to Tatsuoka et al. (2008), but also the degradation of waste due to a high organic content of MSW. The composition of MSW will be changes with degradation process due to MSW generate to CO_2 and methane in anaerobic condition. Therefore, the understanding of the geotechnical properties of MSW will be invaluable in assessing the reliability of facilities constructed with such materials. However, it is very difficult to determine the mechanical properties of MSW due to high the compressibility, heterogeneous composition and the degradation of MSW. Previous studies have discussed the mechanical properties MSW (Landva 1990; Gabr and Valero 1995; Hossain et al. 2003; Hossain and Haque 2009; Reddy et al. 2009a). The results showed that the mechanical properties of MSW vary with age and decomposition. During the design and operation of a bioreactor landfill, the settlement and stability of the landfill are crucial issues. In this type of landfill, leachate recirculation increases the water content and pore water pressure which could lead to landfill instability in the long-term. However, there are few studies about the effect of biodegradation on the mechanical properties of municipal solid waste in a bioreactor landfill. In addition, regarding the impact of biodegradation on the strength of MSW, the results reported by researchers are not consistent. While some researchers pointed out that shear strength decreased with an increase in MSW decomposition (Hossain 2002; Hossain and Haque 2009), other researchers reported an increase in shear strength with decomposition of waste (Reddy et al. 2009a; Reddy et al. 2009b; Machado et al. 2010). Therefore, selection of appropriate shear strength parameters during the waste biodegradation process remains a challenging issue for bioreactor landfill design.

In the case of coastal landfill sites, aging effect on the mechanical properties of waste layer also need to be considered for reclamation. In coastal landfill sites, MSWIA, slag, surplus soil and dredged sand are mainly disposed. For MSWIA, the aging effect in laboratory tests has shown an increase in the shear strength (Sato et al. 2001; Itoh et al. 2005; Towhata et al. 2010), a decrease in hydraulic conductivity (e.g., Doi et al. 2000; Sato et al. 2001; Itoh et al. 2005; Towhata et al. 2010), and an increase of unconfined compression strength (e.g., Doi et al. 2000). The following mechanisms have been proposed to explain the adding effects on MSWIA:

- Hydration and pozzonalic process (Sato et al. 2001; Towhata et al. 2010).
- Self-hardening behavior (Itoh et al. 2005; Towhata et al. 2010)
- Ettringite generation with time (e.g., Doi et al. 2000).

However, there are not available studies about the aging effect of waste mixture in coastal landfill sites. Therefore, this research investigates the aging effect on a waste mixture layer in coastal landfill sites. In this research, the mechanical properties tests for waste mixture samples were conducted after curing several days in simulated surface water in coastal landfill sites. This part also can be considered the creep behavior as well as hydration of waste mixture.

1.2 Objectives and Scope

The aim of this study is to investigate the effect of time dependency on the mechanical properties of waste in landfill sites. The main objectives of this research are:

1) To study the aging effects on the mechanical properties of waste mixture in a coastal landfill site.
2) To evaluate the effects of biodegradation on the mechanical properties of municipal solid waste.

1.3 Outline of Dissertation

This dissertation is divided in seven (7) chapters. The main points and the research methods of this study are listed in Table 1.2. During the experimental work, consolidated undrained triaxial (CU) test and consolidation test, were mainly used for estimating the changes of the mechanical properties of waste with time. The outline of this research is shown in Fig 1.1 and summarized as follows:

1) Chapter 1 presents the objectives of this research and outline the content of this dissertation.
2) Chapter 2 includes a literature review of landfill classification, waste decomposition, and geotechnical issues relate to bioreactor landfill, as well as geotechnical issues related to the utilization of coastal landfills.
3) Chapter 3 describes the aging effects on the mechanical properties of a mixture waste sample that have been cured for up to 180 days in simulated coastal landfill leachate. In order to investigate the mechanical properties, laboratory tests such as consolidation, CU triaxial, Scanning Electron Microscopy (SEM) and X-ray diffraction analysis (XRD) were carried out on waste mixture samples before and after being cured. The author also proposes the mechanism of aging effect on mechanical properties of waste mixture layer in coastal landfills.
4) Chapter 4 discusses the scale effect on shear strength properties of waste mixture in coastal landfill site. In this chapter, a large triaxial test which is 15 cm in diameter and 30 cm in height of specimen was carried out due to the presence of large particles in the waste mixture sample. The comparison between small and large triaxial test results is necessary for better understanding of the shear strength behavior of waste mixture in coastal landfill sites.
5) Chapter 5 discusses the effect of waste biodegradation on mechanical properties of MSW in bioreactor landfills. In this chapter, the lab-scale bioreactor landfills were constructed to simulate a MSW landfill under anaerobic condition. Synthetic MSW (SMSW) was prepared using different types of materials to create an approximate representation of a typical MSW sample in Vietnam. During the test, pH; chemical oxygen demand (COD) of

the leachate and gas production were measured periodically for estimating the current biodegradation phase. Then, SMSW was extracted and tested for physical characteristics, settlement and shear strength properties. Consolidation tests and consolidated undrained (CU) triaxial compression tests were conducted for initial waste and waste after biodegradation in order to estimate the effect of biodegradation on the mechanical properties of waste in a bioreactor landfill.

6) Chapter 6 discusses the results obtained from the experimental results and presents the practical implications of this study.
7) Chapter 7 summarizes the results of this study and suggests further areas of research in this topic.

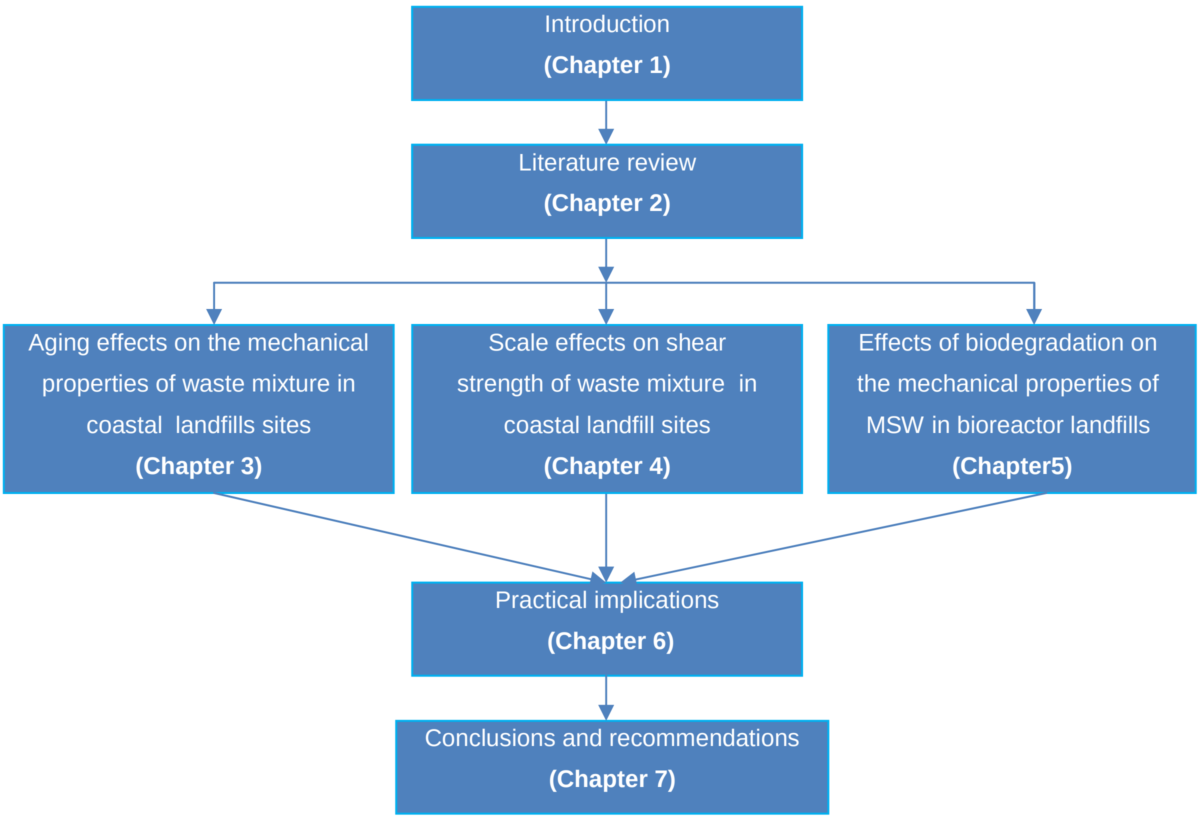


Fig. 1.1 Outline of dissertation

Table 1.3 Main points and research methods in this study

Chapter	Main points	Research methods
3	Mechanical properties of waste mixture in coastal landfill site: • Material: waste mixture collected from a coastal landfill site. • Mechanical properties test: CU triaxial test (50mm x 100mm), hydraulic conductivity • XRD, SEM analysis	Laboratory test and associated analytical method
4	Scale effect on shear strength of waste mixture in coastal landfill site: • Material: waste mixture collected from a coastal landfill site. • Large triaxial test (150 mm x 300 mm) • Comparison of shear strength results on small and large samples	Laboratory test
5	Effect of biodegradation on mechanical properties of municipal solid waste in bioreactor landfills: • Material: synthetic municipal solid waste • Bioreactor tests • Consolidation and triaxial CU test	Laboratory test and associated analytical method

CHAPTER 2: LITERATURE REVIEW

2.1 General Remarks

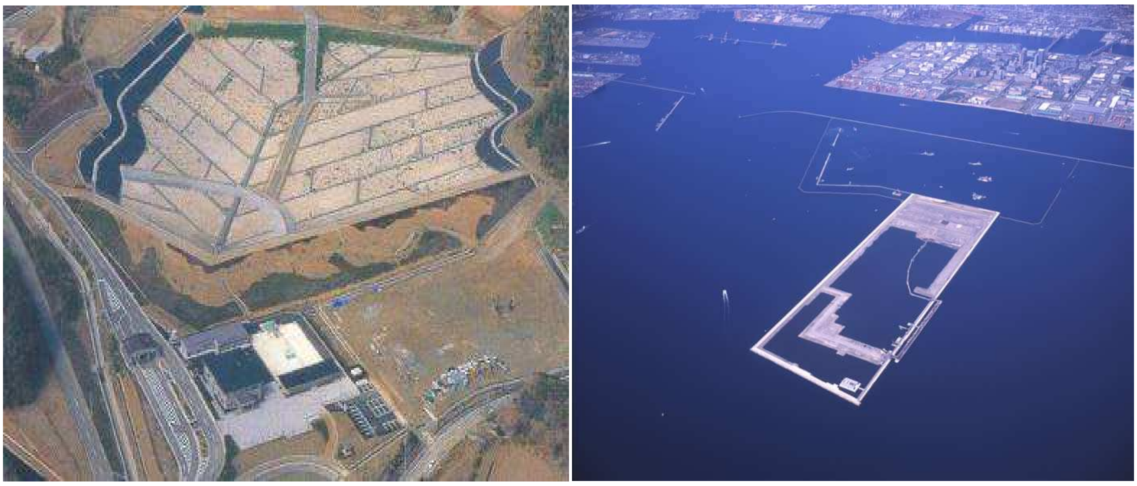
The effective utilization of natural resources is a crucial issue for every country due to population expansion and the consumption of those resources. The production of large amounts of waste makes it difficult to use landfilling as a disposal method due to the lack of available land. Thus, the implementation of 3-Rs programs is important to reduce the amount of waste to be disposed. In addition to this, recycling and the construction of a sound material-cycle society need to be promoted.

Nowadays, as waste generation increases significantly worldwide, a greater demand for both waste collection and innovative treatment options, is required (ADB 2011). The main target of municipal solid waste (MSW) management is to treat the waste in an environmentally and socially acceptable manner, with appropriate clean technologies. This approach could reduce the environmental problems, including air pollution, soil and groundwater contamination, and emissions of greenhouse gases.

The aging effect is an important factor on the mechanical properties of waste in bioreactor landfills and in the mechanical properties of coastal landfill sites. In this research, the aging effect on the mechanical properties of waste is studied. The purpose of this chapter is to briefly introduce (1) a general classification system for landfill sites, (2) the decomposition bioreactor landfill, (3) the aging effects on mechanical properties of waste in bioreactor landfill and (4) the aging effects on the mechanical properties of coastal landfill sites.

2.2 Classification of landfill sites

Landfill sites can be categorized according to their location into inland landfills and coastal landfills as shown in Fig. 2.1. In Japan, inland landfill sites are classified into 3 categories as shown in Fig. 2.2. According to this classification: a) Non-degradable waste landfills are used for reclaiming stable substances (e.g. plastics, metals, concrete, waste rubber, and waste glass; b) degradable and municipal solid waste landfills are used for reclaiming incinerator ash and sludge. In this type of landfill an impermeable cover system is not required, as semi-aerobic and aerobic systems in Japan should allow infiltration to occur in order to achieve the stabilization of landfilled waste for future use after closure; c) hazardous waste landfills are used for hazardous substances, and they required a cement concrete layer to contain the waste (Plata 2009).

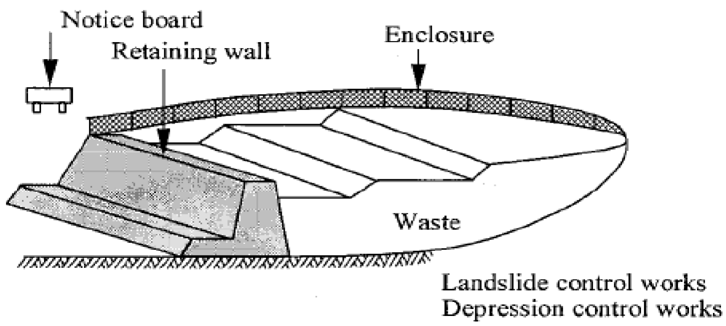


Inland landfill site Coastal landfill site

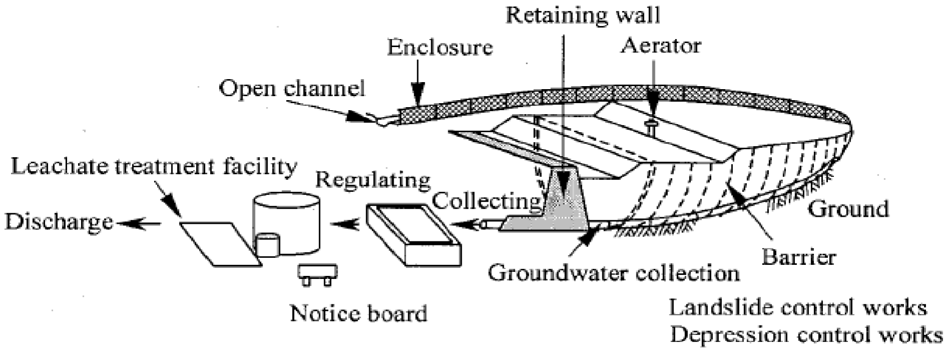
Fig. 2.1 Classification of landfills due to its location

The Standard for landfill sites in Japan allows the utilization of a natural layer with a thickness ≥ 5 m and a hydraulic conductivity ≤ 1x10-7 m/s. If these conditions are not achieved, it requires one of the following three liner systems: (1) two geomembranes (GMs) which sandwich a nonwoven fabric or other cushion material, (2) a GM underlain by an asphalt-concrete layer ≥ 5 cm in thickness with a hydraulic conductivity ≤ $1x10^{-9}$ m/s, or (3) a GM underlain by a clay liner ≥ 50 cm in thickness with a hydraulic conductivity ≤ $1x10^{-8}$ m/s (Kamon and Katsumi 2001).

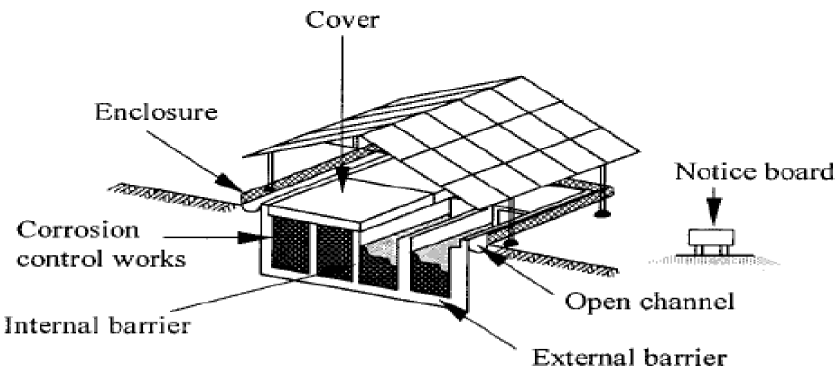
In Japan, due to inland limitation, the locations of landfills have been diversified to coastal areas (Inazumi 2011). The role of coastal landfill sited has been increasing steadily (Inazumi 2011). Coastal landfill sites account for only 2% of the total number of sites, but 28% of landfill volume due to its large capacity (Tanaka et al. 2005).



a) Non-degradable waste landfills



b) Degradable and municipal solid waste landfills



c) Hazardous waste landfills

Fig. 2.2 Types of inland landfill sites in Japan

2.3 Aging effects on the mechanical properties of MSW in bioreactor landfills

This section summarizes a literature review about the aging effects on the mechanical properties of MSW. Previous studies have discussed the mechanical properties of MSW and pointed out that the mechanical properties of MSW vary with age and decomposition (Landva 1990; Gabr and Valero 1995; Hossain et al. 2003; Hossain and Haque 2009; Reddy et al. 2009a).

2.3.1 Decomposition of MSW in bioreactor landfills

Decomposition of waste in a landfill site is usually explained as a four-phase time sequence (Barlaz et al. 1989). The processes that occur at each phase of decomposition can be summarized as follows:

Phase 1- Aerobic Phase: After the initial placement of the waste, the oxygen present in the voids is consumed for the CO_2 production. During the aerobic phase, leachate strength is relatively low and the gas produced is mainly CO_2 and N_2 with no methane production.

Phase 2 - Anaerobic Acid Phase: In this phase carboxylic acids accumulate and pH decreases. The gas produced is still mainly CO_2 with little methane production at the end of the phase. The decomposition of solid is estimated to be between 15-20% based on laboratory data.

Phase 3 - Accelerated Methane Production Phase: An increase in pH and methane production, a decrease in carboxylic acid concentration and a methane concentration of 50-60% marks the onset of this phase. Due to the decrease in carboxylic acid accumulation, pH increases significantly. Solids decomposition occurs in this phase but most of the methane is due to depletion of carboxylic acids accumulated in phase 2.

Phase 4 - Decelerated Methane Production Phase: The rate of methane production decreases but the methane and carbon dioxide concentrations remains the same as in the previous phase, about 60% and 40% respectively. The rate of cellulose and hemicelluloses decomposition reaches its maximum at this stage. In the earlier phases refuse decomposition leads to the accumulation of carboxylic acid whereas in the fourth phase the rate of polymer hydrolysis exceeds the other phases and no accumulation of carboxylic acids are observed. Solid decomposition is 50-70% in this phase depending on the methane production and operational management practices.

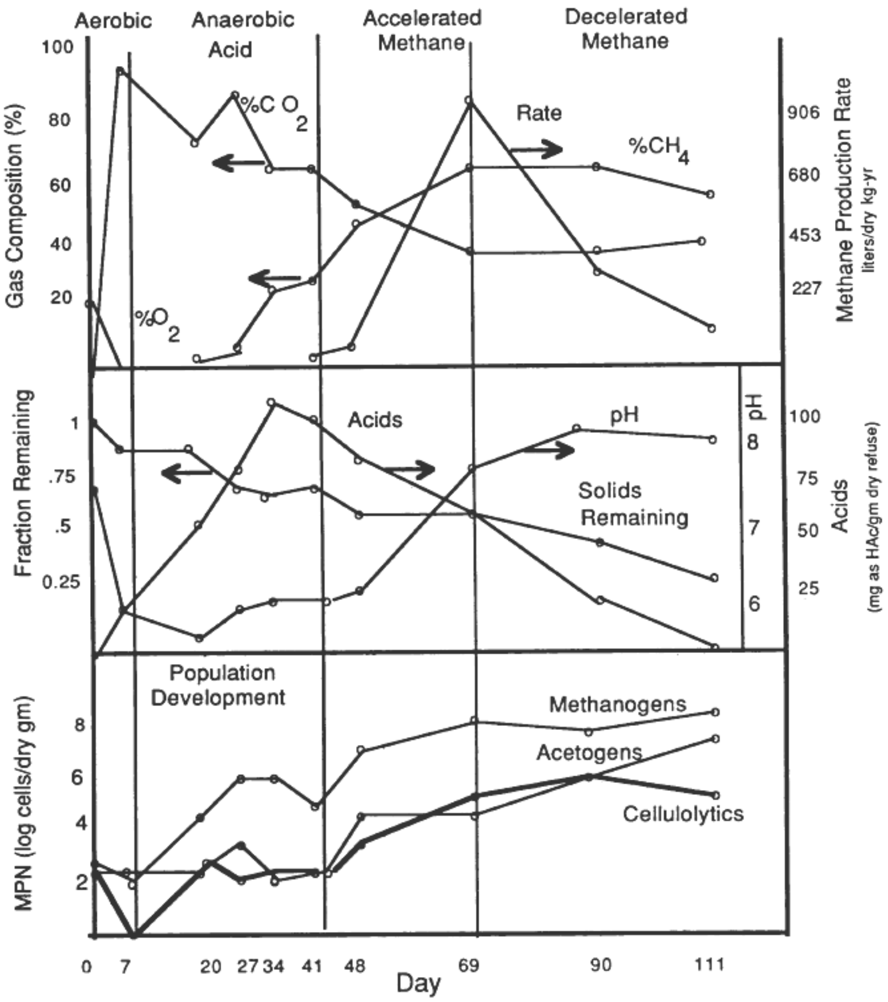


Fig. 2.3 Summary of observed trends in refuses decomposition with leachate recycles (Barlaz et al. 1989)

The pH value of leachate is another indicator of the decomposition stage (Hossain 2003). The optimum pH for anaerobic systems ranges between 6.5 and 7.6 (Parkin and Owen 1986). Gas generation and decomposition rates have been reported to be highest at near neutral pH levels (Alyousfi et al. 1993).

In general, the pH of leachates range between 4.7 and 8.8 for conventional landfills (Kjeldsen et al. 2002) and from 5.4 to 8.6 for bioreactor landfills (Hossain 2002). Initially, the pH of leachate may be neutral; however, after the onset of anaerobic conditions, the pH drops especially during the acid forming phase. This drop in pH is most likely caused by the volatile fatty acid production and their accumulation in the leachate (Townsend et al. 2004). The pH, however, will tend to become neutral as methanogens consume these acids.

In the case of leachate recirculation in a bioreactor landfill, MSW decomposition is accelerated and this increases potential instability in the landfill. Therefore, the study of the effects of MSW decomposition and geotechnical properties in a bioreactor landfill are of high relevance.

2.3.2 Aging effects (biodegradation) on the mechanical properties of MSW in bioreactor landfills

In contrast to the traditional landfill approach, a bioreactor landfill operates to rapidly transform and degrade the organic components of the waste mass (see Fig. 2.4). The bioreactor landfill accelerates the MSW decomposition and its stabilization by re-circulating the leachate (Reddy and Bogner 2003; Elagroudy et al. 2008; Valencia et al. 2009). Leachate recirculation in a bioreactor landfill considerably changes the geotechnical characteristics of the waste, and therefore increases the concern for waste stability (Reddy and Bogner 2003). MSW settlement and shear strength are discussed in the following sections.

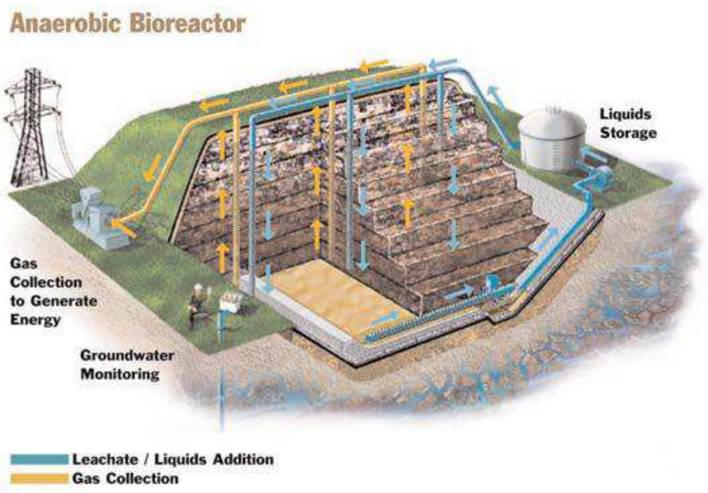


Fig. 2.4 Anaerobic Bioreactor (Waste Management, March 2000, pp 25-27).

2.3.2.1 Settlement of municipal solid waste in bioreactor landfill

The MSW settlement is very important for a bioreactor landfill during its operations. The MSW settlement is difficult to determine due to the heterogeneous, anisotropic and unsaturated condition of the MSW. The settlement of MSW depends mainly on the amount of organic content, initial density, fill height, stress history, water content, composition and waste decomposition (Edil and Berthouex 1990). The mechanisms of settlement in MSW are not clear and many researchers have been focused in trying to identify them. The settlement of MSW is commonly estimated using the theory of one-dimensional consolidation (Fassett et al. 1994; Hossain 2003), with the total settlement divided into primary and secondary component (Sowers 1973; Fassett et al. 1994; Hossain et al. 2003).

There are various equations that explain the settlement undergoing degradation. Sowers (1973) presented the estimation of settlement as the following equations:

For initial compression,

$$S_i = \frac{\Delta_q H_0}{E_s} \tag{2.1}$$

where, S_i is the settlement due to initial compression (m); Δ_q is stress increase in stratum (kPa); H_0 is initial height of the MSW (m); E_s is the modulus of elasticity (kPa).

For primary compression according Terzaghi theory,

$$S_p = H_i C_c' log[(\sigma_0 + \Delta\sigma)/\sigma_0] \tag{2.2}$$

where, S_p is the settlement due to primary compression (m); H_i is the height of refuse after initial compression (m); C_c' is modified primary compression index; σ_0 is existing overburden pressure at the middle level of the layer (kPa); $\Delta\sigma$ is increment of overburden pressure at middle level of the layer (kPa).

And for secondary compression,

$$S_s = H_p C_\alpha' log[t/t_p] \tag{2.3}$$

where, S_s is the settlement due to secondary compression (m); H_p is the height of refuse after primary compression (m); C'_α is modified secondary compression index; t is the time; t_p is time for primary compression to occur.

Many researchers have noted that the MSW settlement decreases as MSW degradation increases. For example, Wall and Zeiss (1995) conducted a study to evaluate the effects of biodegradation on settlement and to study time reduction by applying leaching recirculation in the landfills. They observed that biodegradation has very little effect on the secondary settlement rates. Total mass of solids decomposed during the test period (250 days) was 1 % whereas the secondary settlement at the same period accounted for 4 % deformation. The results presented by Gabr and Valero (1995) showed a high compressibility of waste. Typical values of its modified primary compression index (C'_c) are in the range of 0.2 to 0.5 depending on the stress level, whereas rate of compression index, C'_α was in the range of 0.2% to 3%. It also appeared that C'_α increased with increasing organic content. Similar results also showed that compression ratio decreased with decreasing organic fraction (Sowers 1973; Chen and Lin 2009) as well as with the increasing contribution of incompressible materials. Chen and Lin (2009) reported trends of decreasing C'_c with increasing waste depth and increasing waste age (i.e., waste decomposition).

However, other researchers have showed an opposite relationship between MSW and waste decomposition with the compression index, C'_c increasing with waste decomposition. For example, Hossain (2003) conducted a test with eight 4 L reactors for both conventional landfill and bioreactor landfills. The reactors were filled with refuse to prepare samples at different stages of decomposition for compressibility testing. The state of decomposition was quantified by the methane yield and the cellulose C plus hemicellulose (H) to lignin (L) ratio ((C+H)/L). The coefficients of primary compression (C_c) for bioreactor samples showed an increasing trend with decreasing (C+H)/L ratios. C_c increased from 0.16 to 0.36 as (C+H)/L decreased from 1.29 to 0.25. The creep index range was estimated at 0.02–0.03 for bioreactor samples in various states of decomposition. The magnitude of the biological degradation index ($C_{\beta i}$) depended on the degradation phase with the highest value of 0.19 obtained during the phase of accelerated methane production.

In this research the modeled for long-term settlement with three terms is presented in Eq. (2.4)

$$\frac{\Delta H}{H} = C_{\alpha i} \ \log\left(\frac{t_2}{t_1}\right) + C_{\beta} \ \log\left(\frac{t_3}{t_2}\right) + H.C_{\alpha f} \ \log\left(\frac{t_4}{t_3}\right) \tag{2.4}$$

where $C_{\alpha i}$ =compression index, which is a function of stress level and degree of decomposition (~0.03); t_1 =time for completion of initial compression (~10-15 days); t_2=time duration for which compression is to be evaluated (~100 to 2,000 days); C_{β}=biodegradation index (~0.19); t_3=time for completion of biological compression (~3,500 days); $C_{\alpha f}$=creep index; and t_4=time for the creep at the end of biological degradation. A similar behavior of MSW settlement increasing with degradation was also confirmed by Reddy et al. (2009a). They determined the changes in settlement of a MSW landfill which was subjected to leachate recirculation for about 1.5 years. The authors pointed out that due to the low amount of leachate recirculation; the extent of MSW degradation was minimal, leading to only minor differences between the properties of fresh and landfilled MSW.

Overall, past researches have not systematically characterized the change in waste compressibility as a function of degradation and the results of MSW settlement related with MSW decomposition are not consistent (See Table 2.1)

Table 2.1 Summary of primary and secondary compression index from various researches

Aged waste (years)	Modified primary compression index	Modified secondary compression index	Author
-	-	0.02	Sowers (1973)
15-30	0.2-0.5	0.002-0.003	Gabr and Valero(1995)
Fresh	-	0.004	Wall and Zeiss (1995)
Fresh	0.16-0.36	0.02-0.03 C_{β}=0.19	Hossain (2003)
-	-		
Fresh waste	0.24-0.33	-	Reddy (2009a)
1.5	0.19-0.24	-	

2.3.2.2 Shear strength of municipal solid waste in bioreactor landfills

Shear strength of MSW is an important property of solid waste for landfill stability analysis (Hossain and Haque 2009; Reddy et al. 2009d). Post-failure investigations have highlighted some common triggering factors such as high pore pressures (resulting from leachate injection or excessive infiltration due to poor surface drainage) and inadequate interface shear strength (waste-foundation soil, waste-geosynthetics or within composite liner system).

Table 2.2 summarizes of various landfill failure events and an example of landfill failure in the Philippines was shown in Fig. 2.5.

Table 2.2 Summary of various landfills failure events.

Year	Landfill location	Q (m^3)	Comments	References
1984	North America (Unlined)	110,000	Single rotational failure. Heavy rainfall for 3-days.	Koerner & Soong (2000)
1996	Rumpke ,USA	1,200,000	Translational failure. Mobilization of post peak shear strength in the brown native soil was the suggested primary reason for failure.	Eid et al. (2000)
2000	Payatas, Phillipines (Unlined)	15000	Rotational failure. Precipitation ten days prior to the incidence. The slope failure due to gas-pore water interaction in saturated waste.	Merry et al. (2005)
2005	Bandung, Indonesia (Unlined)	2,700,000	Translational failure happened after 3 days of heavy rain. Failure was triggered by water pressure in the soft subsoil in combination with a severe damage of tensile elements due to a smouldering landfill fire	Koelsch et al (2005)

Various researches have tried to analyse the shear strength of MSW. Determination of shear strength properties for MSW is difficult due to the heterogeneity of MSW, time-varying properties, and strain incompatibility between the MSW and underlying materials (Eid et al. 2000). MSW shear strength parameters reported in the literature vary widely with friction angles going from 10° to 53°, and cohesion values ranging from 0 to 67 kPa (Landva 1990; Eid et al. 2000; Hossain and Haque 2009). In the case of a bioreactor landfill, the accelerated decomposition of the MSW could considerably affect the shear strength and therefore increase the concern for waste stability (Hossain and Haque 2009). Moreover, in a bioreactor landfill, water content increases with leachate recirculation, which may change the effective shear strength. In this case, undrained strength should be suitable for estimating the landfill stability.

Regarding MSW shear strength, results from previous studies shows opposite results. On one side, the following studies showed that MSW shear strength decreases with an increase of MSW decomposition (see Fig. 2.5). For example, a direct shear test was conducted by Landva and Clark (1991) on MSW samples from different landfills in Canada. The results showed that cohesion and friction angle for a MSW sample, that was left for a period of one year in a container were reduced from 23 to 10 kPa and 42° to 9°, respectively. This change may not be fully attributed due to decomposition effects. Gabr and Valero (1995) observed that for MSW samples between 15 to 30 years old, the cohesion value decreased with the moisture content. The change that was measured in the angle of internal tensile stress depended on the age of waste. Similar behavior could be found in the results reported by Hossain (2002). The author estimated the shear strength parameters based on the degree of decomposition using direct shear test. The state of decomposition was quantified by the methane yield related to the cellulose (C) plus hemicellulose (H) to lignin (L) ratio $(C + H)/L$. It was also found that at the initial stage of decomposition, when (C+H)/L ratio is 1.29; the friction angle was 32º. However, at a fully decomposed state (i.e., when (C+H)/L is 0.25) the friction angle was 24º.

Fig. 2.5 Aerial view of Payatas landfill failure in Philippine (Zekkos 2005).

The results presented by Hossain and Haque (2009) also had a similar trend. The authors conducted laboratory-scale bioreactor landfills which simulated MSW decomposition phases. A number of consolidated drained (CD) triaxial tests were performed to evaluate the shear strength of MSW. The test results showed a remarkable decrease in friction angle with decomposition. At 20% strain level, the friction angle decreased from 26.7° in Phase I, to 19° in Phase IV. The increased percentage of plastic materials in the MSW composition present in the final stages of decomposition created more potential sliding surfaces, and decreased its shear strength.

On the other side, other researchers have also reported an increase in shear strength with decomposition of waste (Machado et al. 2008; Reddy et al. 2009c; Machado et al. 2010). The change of MSW properties with decomposition can be illustrated by the data of Machado et al. (2008) in Fig. 2.7. In this figure a reduction of about 24% in the modulus of elasticity and of about 9% in the ultimate tension strength of plastic material was observed after 4 years since deposition was observed. The results presents by Reddy et al. (2009a) also showed a trend of decreasing cohesion and increasing angle of friction with the age of MSW. The study determined the changes in shear strength of landfilled MSW which was subjected to leachate recirculation for about 1.5 years. Based on triaxial CU tests on landfilled MSW, the effective stress parameters, cohesion and friction angle were 34 kPa and 23°, respectively, while the values for 15 years old MSW were 38 kPa and 16°.

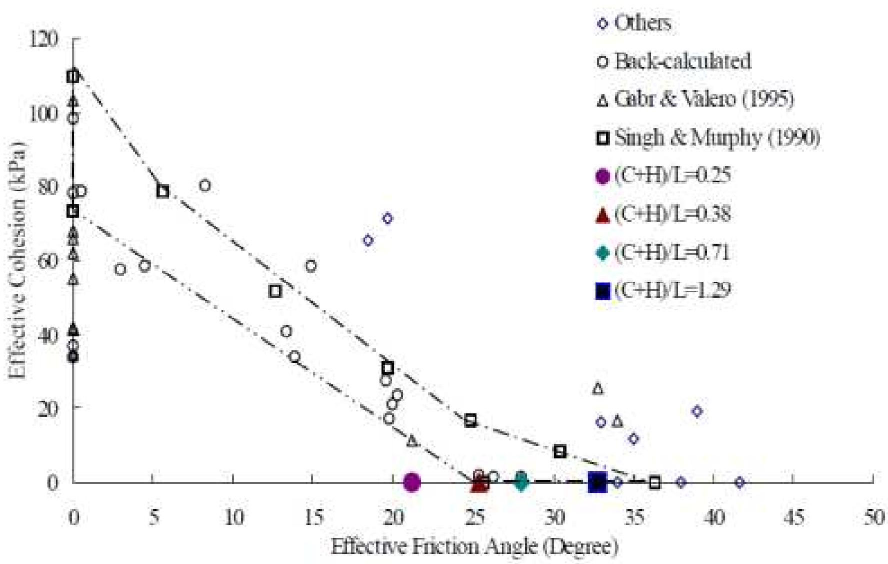


Fig. 2.6 Rate of change in friction angle at different stage of decomposition (Hossain, 2002)

Table 2.2 Summary of shear strength parameters from previous researchers

Aged waste (years)	**Friction angle (°)**	**Cohesion (kPa)**	**Type of experiment**	**Author**
Fresh	42	23	Direct shear test	Landva and Clark (1991)
1.0	9	10		
15 – 30	34	17	CU triaxial test	Gabr and Valero(1995)
Initial stated of decomposition	32	0	Direct shear test	Hossain (2002)
Fully decomposed state	24	0		
Initial stated of decomposition	26.7	11.2	CD triaxial test	Hossain and Haque (2009)
Fully decomposed state	19	2.4		
Fresh	23	34	CU triaxial test	Reddy 2009a
1.5	16	38		

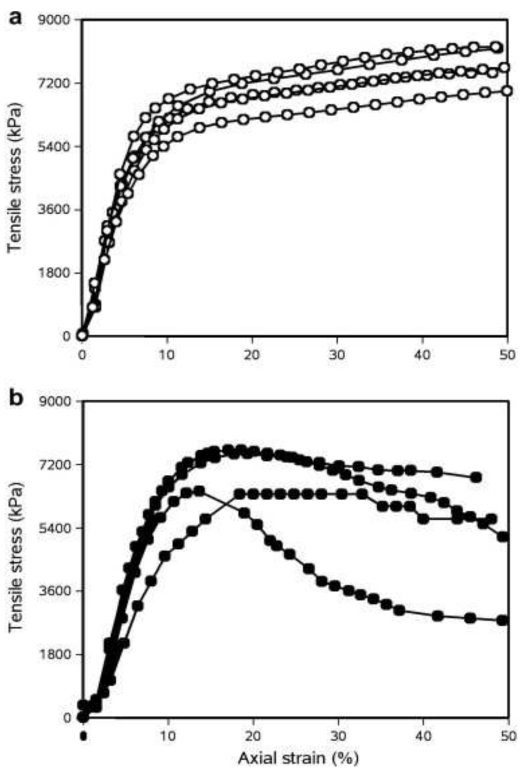


Fig. 2.7 Stress–strain curves: (a) new samples; (b) 4 years old samples **(**Machado et al. 2008).

Due to the differences in the results obtained on the topic by various researches, it is relevant to estimate the effect of biodegradation on the settlement and shear strength of MSW in a bioreactor landfill.

2.4 Geotechnical considerations of coastal landfill sites

In the case of coastal landfill site, aging effects on mechanical properties of waste mixture may be very important. In coastal landfill, MSWIA, slag, surplus soil and dredged sand are mainly disposed and become mixture of waste. However, there is no study related to aging effects of waste in coastal landfill site. There is need to study aging behavior and discover the mechanism for waste mixture in order to utilize coastal landfill sites after closure. This section describes the MSWIA composition and the types of coastal landfill sites in Japan and types of waste that is disposed in them. In addition, a summary of previous researches on the aging effects on mechanical properties of waste mixture is presented.

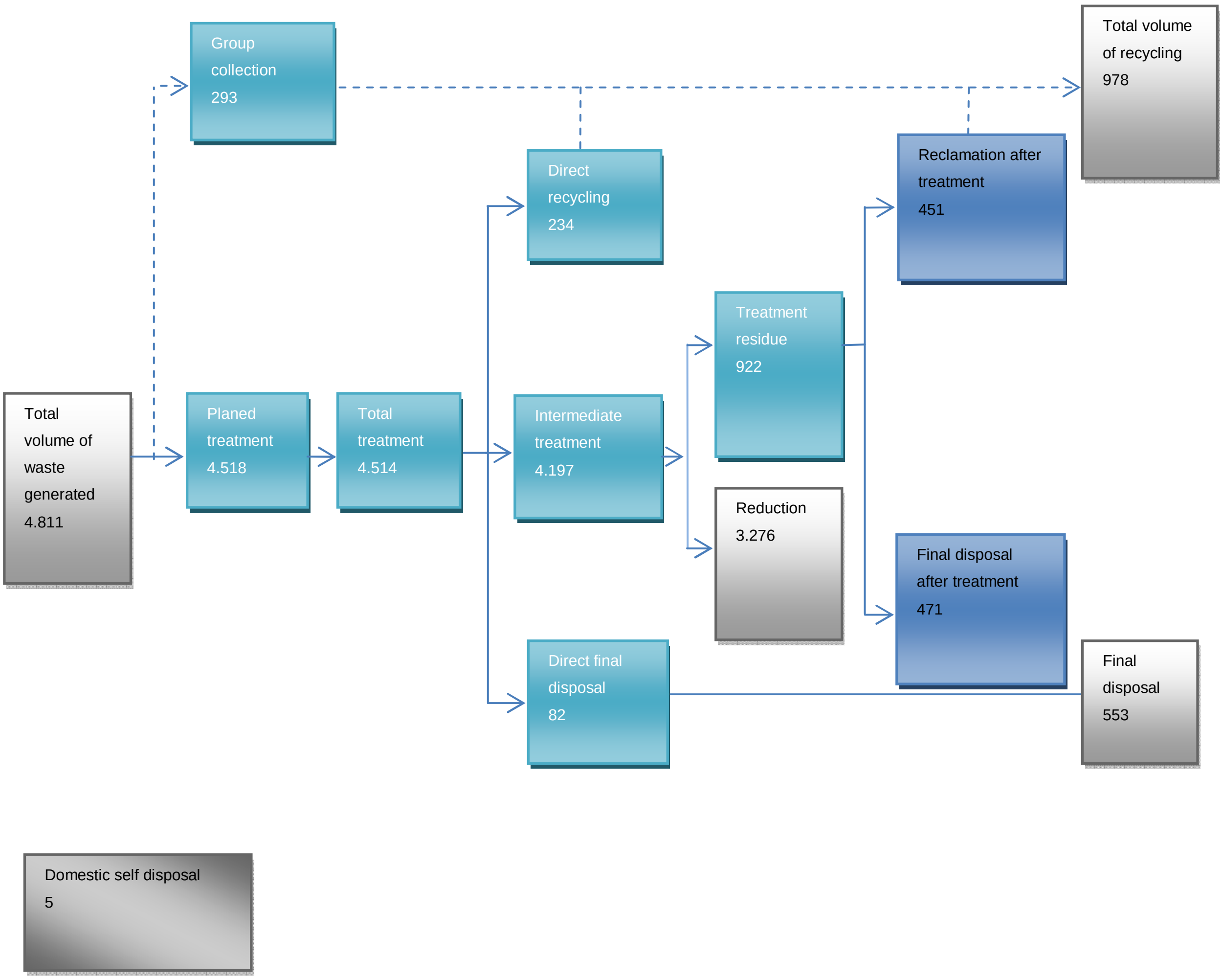
2.4.1 Municipal solid waste incinerator ash

Billions of tons of MSW are produced every year worldwide. Waste management and utilization strategies are a major concern in many countries. Incineration is a common technique for treating waste, as it can reduce waste mass by 70% and volume by up to 90%, as well as providing recovery of energy from waste to generate electricity (Lam et al. 2010). Generally, municipal solid waste incineration (MSWI) produces two main types of ash, that can be grouped as bottom ashes (BA) and fly ashes (FA). The chemical and physical characterization of the ash will depend on the compositions of the raw MSW, the operational conditions, the type of incinerator and air pollution control system design. Table 2.4 shows the chemical composition of MSWBA from different incineration facilities. It can be observed that the major elements are Si, Al, Fe, Mg, Ca, K, Na and Cl and the most common oxides ash found in bottom ash are SiO_2, Al_2O_3, CaO, Fe_2O_3, Na_2O, K_2O.

Table 2.3 Bulk chemical composition of MSWI bottom ash from different incineration facilities (Wei et al. 2011)

Major/minor composition (w_t %)	MSWI bottom ash samples			
	R-04	S-08	S-09	F-09
SiO_2 (IV)	31.93	43.69	37.25	36.49
Al_2O_3	16.65	14.03	15	14.48
Fe_2O_3 (III)	5.97	6.21	5.16	7.89
TiO_2 (IV)	1.45	1.51	1.63	1.63
MnO (II)	0.08	0.08	0.09	0.1
P_2O_5 (V)	0.02	<0.01	<0.01	<0.01
CaO	33.4	24.67	31.33	28.5
MgO	3.33	2.18	2.58	2.71
Na_2O	2.53	2.46	2.31	2.53
K_2O	0.85	1.5	1.01	0.99
C	2.22	2.16	1.72	2.53
Cl	1.08	1.27	1.57	1.8
S	0.4	0.21	0.35	0.32
Trace composition (mg/kg)				
Zn	3193	3098	3295	3253
Cu	2321	2288	1710	2481
Pb	687	1149	1079	698
Cr	393	158	441	363
Ni	105	79	133	119
Ba	1126	942	835	904
Sb	4	5	4	4
Sn	111	81	64	13
Sr	271	276	362	319
As	<1	<1	<1	<1
Zr	<5	<5	<5	<5
V	1	2	3	2
Cd	1	<1	<1	1
Co	5	8	7	9

In Japan, about 48 million tons of MSW were discharged in fiscal year 2008 (see Fig. 2.8) and about 80% of this amount was incinerated. Incineration of MSW is very effective in reducing the volume and assisting in the decomposition of hazardous chemical compounds.



Unit: ten thousand tons

Fig. 2.8 Waste flow in Japan in 2008 (Ministry of the Environment, 2010)

Recently, the increasing percentage of MSWIA has changed the composition of the waste that is disposed (Plata 2009). In 2004, more than 75% of MSWIA were mainly disposed at coastal landfill sites (Shimaoka et al. 2007). Land reclamation in coastal landfill sites has been carried out on large scale in Tokyo and Osaka bay (Aburatani et al. 1996). In the case of Osaka bay Phoenix project, it has a strict standard for the waste to be accepted, e.g. waste must be non-hazardous, ignition loss should be less than 15% and water content in percent of dry weight up to 30%; these conditions help to improve and facilitate future land utilization. Types of waste accepted into coastal landfill site of the Phoenix Project include MSW, industrial waste, surplus soil and dredged sand (See Table 2.4).

Table 2.4 Type and amount of waste of the Phoenix Project (Unit: millions m^3)

Landfill location name	**Municipal solid waste**	**Industrial waste - disaster waste**	**Surplus soil**	**Dredged sand**	**Total**
Izumiotsu coastal landfill site	390	720	1,270	720	3,100
Amagasaki coastal landfill site	220	290	700	390	1,600
Kobe coastal landfill site	580	620	300	0	1,500
Osaka coastal landfill site	540	580	280	0	1,400
Total	1,730	2,210	2,550	1,110	7,600

In recent years, the number of coastal landfill sites in Japan has increased due to the limitation of inland space for waste disposal (Katsumi et al. 2009). Coastal landfill sites account for only 2% of the total number of disposal sites in Japan, but receive nearly 30% of the waste produced because of their relatively larger size (Tanaka et al. 2005). In coastal landfill sites, natural clay deposit of more than 5 m in thickness and a hydraulic conductivity not exceeding $1x10^{-7}$ m/s, play the role of bottom hydraulic barrier. The guideline for containment systems to be used in coastal landfill has been published by the Japanese Ministry of Transport (Katsumi et al. 2009). The barrier systems to be used in coastal landfill sites are presented in Fig. 2.9 (Katsumi et al. 2009). The caisson type can be used for handling toxic residues, but it has a shallow penetration depth. The double sheet-pile type quay wall has a good penetration depth and has proven to be practical from the constructive and economic point of view. The rubble mound is used for stable and non-toxic waste material (Inazumi et al. 2008).

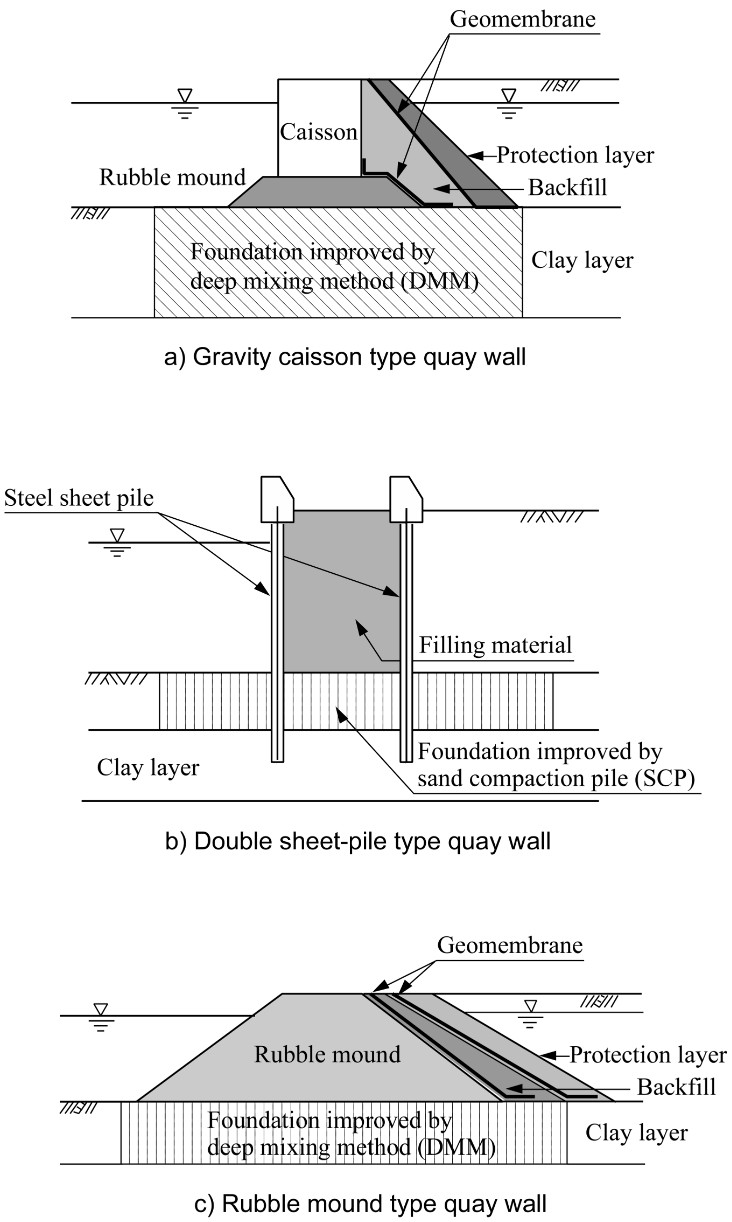


Fig. 2.9 Side barrier systems for Japanese coastal landfills (Adopted from Katsumi et al. 2009)

2.4.2 Aging effects on the geotechnical properties waste in coastal landfill sites

To ensure future reclamation of coastal landfill sites areas, it is necessary to thoroughly understand the geotechnical properties of waste mixture layer in coastal landfill sites. However, there is limited information on the geotechnical properties of waste mixture in coastal landfill sites. Previous studies show that the hydration of an ash sample with calcium versus time resulted in a decrease of permeability and compression of the ash material (Yoichi et al. 2000), and also that ash-water interaction caused transformation of its physical, chemical, mineralogical and geotechnical characteristics (Singh and Kolay 2002). Das and Yudhbir (2006) presented the geotechnical properties of low calcium and high calcium fly ash. The results suggested that the gain in strength with time (self-hardening) of high calcium fly ash was 230 times higher than the low calcium fly ash due to hydration of reactive minerals and glassy phase and formation of ettringite, calcite and calcium silicate hydrate. Towhata et al. (2010b) indicated that when MSWIA were submergence in water, cementing material covered the grains of ash reducing the pore structure of ash which reduced which in turn decrease the hydraulic conductivity of the MSWIA sample.

In the case of coastal landfills, MSWIA, slag and soil are disposed in them and the result is a waste mixture. However, there is no research available about the geotechnical properties of waste mixture in coastal landfills. Therefore, in this research, the aging effect on the mechanical properties of the waste mixture layer in coastal landfills is discussed in detail in chapter 3. The results could be used to improve land utilization after coastal landfill closure.

CHAPTER 3: AGING EFFECTS ON THE MECHANICAL PROPERTIES OF WASTE MIXTURE IN COASTALLANDFILL SITES

3.1 General Remarks

Coastal landfilling is an important method for disposal of municipal solid waste incinerator ash (MSWIA), slag, soil, etc. in Japan. More than 75% of MSWIA were disposed at coastal landfill sites in 2004 (Shimaoka et al. 2007). In general, coastal landfill sites are located at strategic points in the port areas of Tokyo and Osaka with relatively easy access from the metropolitan areas. Coastal landfill reclamation is a key option considering Japan's land limitation; for this reason, it is important to understand the strength and deformation properties of the waste mixture layers and the bearing capacity of the ground. Limited research is available regarding the engineering properties of the waste mixture layers in coastal landfill sites and the geotechnical characteristics of waste mixture that includes incinerator ash, slag, and surplus soil. One of the examples is Osaka Bay Phoenix Project, which is a coastal landfill project that started in 1990 and has 45 million m^3 of total capacity; soil exploration was carried out at the MSW landfill zone of Amagasaki offshore disposal site to determine the physical and dynamic properties (Aburatani et al. 1996). In this research, the total unit weight of the waste layer in the Osaka Bay varies between 15-18 kN/m^3 depending on the depth of waste layer and the internal friction angle ranges from 24.5° to 35°. The reclaimed land is considered equivalent to loose alluvial sandy soil with an average value of standard penetration (N-value) of 4.5.

Time dependency on the waste mixture properties may be important. However, there is also limited information about the changes on the geotechnical properties of the waste mixture with time. A consolidated drained triaxial test was carried out on waste incinerator ash under three different conditions including dry, wet and water immersed conditions (Sato et al. 2001). The results showed an increase in the strength of the incinerator ash samples with longer curing periods due to the hydration of the samples and the pozzolanic reactions. Moreover, an increasing strength in the incinerator ash samples that were submergence in water was also reported by Itoh et al. (2005) and Towhata et al. (2010a). The results of these researchers showed a reduction in the pore structure of ash and a decrease in the hydraulic conductivity of incinerator ash samples. A study carried out by Doi et al. (2000) showed that the unconfined compression strength improved with increasing time, while hydraulic conductivity decreased together with a reduction in the compressibility of incinerator ash samples. The authors pointed out that ettringite generated with time caused an increase in the strength of material.

In coastal landfill sites, waste mixture is submerged in seawater and the geotechnical properties of waste are expected to change with curing time. However, there is no available research that evaluates the shear strength and deformation properties of the waste mixture when waste mixture samples interact with simulated coastal landfill leachate for a long time. Therefore, this study investigates the aging effect on the mechanical properties of waste samples submerged in simulated surface water in coastal landfill site with time. In this research, waste mixture specimens were collected before disposing them in the coastal landfill site and samples were cured in a simulated leachate for different time periods to simulate conditions in a coastal landfill site. A series of triaxial consolidated undrained compression tests (CU) and hydraulic conductivity tests were carried out on waste mixture samples before and after they were cured in seawater. Scanning electron microscope (SEM) and X-ray diffraction (XRD) analysis were also conducted for further understanding of the changes in geotechnical properties of waste mixture after being cured in seawater. Based on the experimental results and observations, the interaction of waste mixture with leachate is discussed in this chapter.

3.2 Materials and methods

3.2.1 Materials

The waste mixture samples and the simulated water in coastal landfill site employed in this study were obtained from the coastal landfill site in Osaka Prefecture. The waste mixture samples were collected before being disposed at the coastal landfill site. Approximately 200 kg of wet waste mixture sample include incinerator ash; slag and surplus soil, etc. were collected and then dried in a room with an average temperature of 20^{o}C. After that, large pieces such as glasses or rocks were removed and the sample was sieved with 9.5mm opening sieve and set aside until use. Figure 3.1 shows the particle size distribution of the waste mixture sample, determined according to JIS A1204. The grain size distribution was 85.9 % sand (>0.075 mm), 8.1% silt (0.005–0.075 mm) and 6% clay (<0.005 mm). The uniformity and curvature coefficients were 127.8 and 2.63, respectively. The material was well graded with a particle size distribution similar to SG-F (sand gravely with fine particle) following the JGS 0051. The specific gravity of the waste mixture sample was 2.67. X-ray florescence Spectroscopy (XRF) was performed to determine the chemical composition of the waste mixture samples. The chemical composition of the sample is shown in Table 3.1. The main components of the sample are CaO; Fe_2O_3 and SiO_2. The XRF shows that lime (CaO) is the main component of the sample (51.6 %) and it is related to the hydration ability of the sample.

To prepare a leachate that simulates the surface seawater conditions in a coastal landfill site, 30 L of water retained in the coastal landfill site which collected in Osaka Prefecture, were mixed with waste mixture in a tank with a waste mixture -water ratio of 1:10 by mass. The mixture was stirred daily for 7 days and then it was filtered through a sieve of 75 μm opening. After that, the pH and the calcium concentration of the seawater were measured and the results showed that the calcium concentration and the pH of the seawater were 1850 ppm and 7.95, respectively. To simulate conditions in a coastal landfill site, waste mixture samples were cured in simulated water in coastal landfill site for up to 180 days.

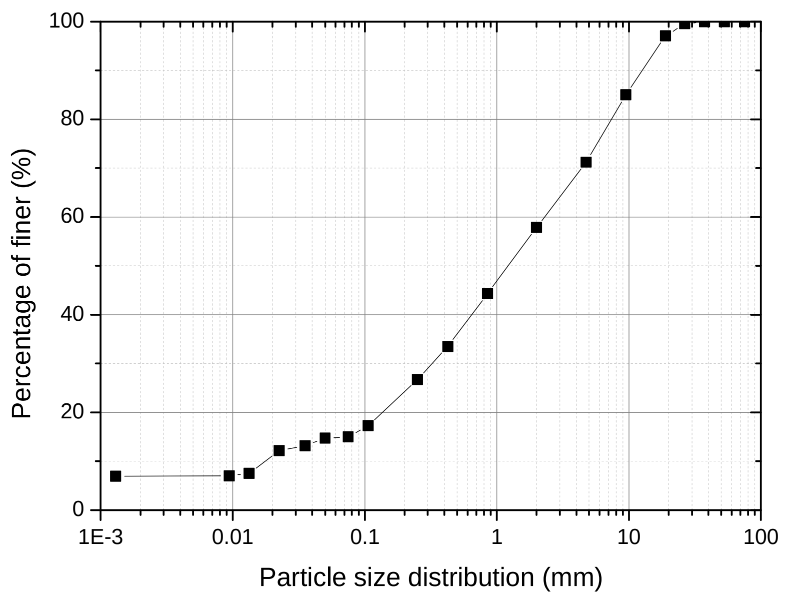


Fig. 3.1 Particle size distribution of waste mixture samples

Table 3.1 Chemical composition of waste mixture sample (%)

CaO	**Fe_2O_3**	**SiO_2**	**Al_2O_3**	**TiO_2**	**SO_3**	**K_2O**	**ZnO**	**Cr_2O_3**	**MnO**	**CuO**
51.61	20.40	9.11	4.28	3.30	2.77	1.66	1.87	1.57	0.54	0.52

3.2.2 Methods

3.2.2.1. Preparation of MSWIA specimens

In this study, 27 specimens were prepared and tested. All specimens were prepared by compacting 5 layers of waste mixture in to a split cylindrical mold (50 mm diameter and 100 mm in height) 80% of maximum dry density (1.28 g/cm^3) with optimum water content of 34.5% according to the value obtained from the Standard Proctor Compaction Test (Fig. 3.2).

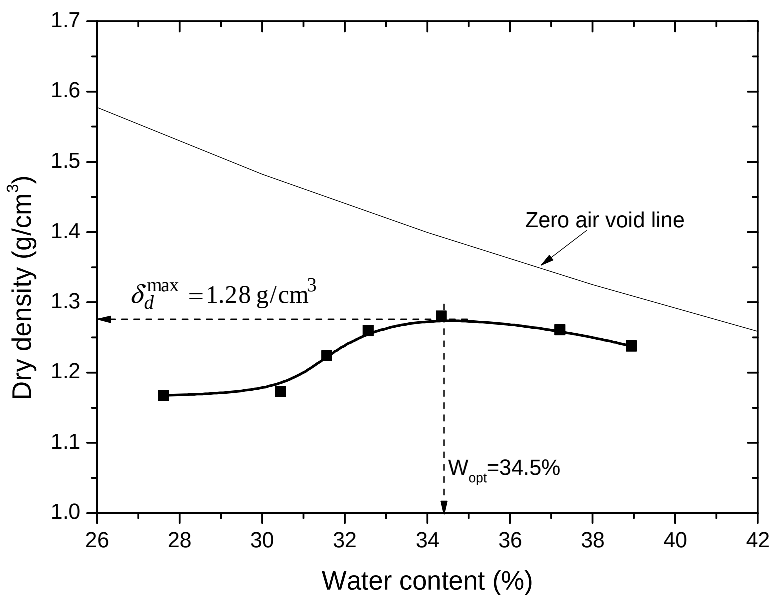


Fig. 3.2 Compaction curve for waste mixture samples

As a result, the wet density of the specimens was approximately 1.6 g/cm^3, which was within the range of the in situ value in a typical coastal landfill site. As shown in Table 3.2, geotechnical tests were conducted for two series of samples: series A (A1-A3) for initial samples and series B (B4-B24) for sample that were cured in seawater. For series A, CU and hydraulic conductivity tests were conducted after compacting without being cured in simulated leachate. For series B, compacted samples were removed from split cylindrical mold and then fixed with two pieces of a half acrylic mold (50 mm diameter and 100 mm in height). Then, the upper and lower surfaces of the specimen were placed on filter paper and porous stone to allow water intake and drainage during curing time. These samples were saturated and de-aired for 24 hours in a vacuum desiccator and then cured for a predetermined period of time in a seawater tank with an average room temperature of 20 ± 2^{o}C. Consolidated-undrainded triaxial and hydraulic conductivity tests were conducted on the samples after 7, 14, 28, 60, 90, 120, 150, and 180 days of curing time. Consolidated-undrainded triaxial test with pore water pressure measurement were carried out on waste mixture specimens. These specimens were saturated by applying a vacuum procedure to keep a constant confining pressure of 20 kPa (Rad and Clough 1984). After reaching the final step (-70 kPa for cell pressure and -90 kPa for sample pressure) de-aired water was circulated into the specimen for 3 hours and then sample pressure and cell pressure were reduced to -20 kPa and 0 kPa respectively. Back pressure was increased step by step until it reached 240 kPa and cell pressure was 220 kPa. After that, pore pressure coefficient (B-value) was checked to have a B-value larger than 0.95 and ensure samples were fully saturated. As detailed in Table 2, specimens were consolidated with an effective confining pressure of 50, 100 and 150 kPa and sheared at a constant strain rate of 0.5%/min until 15% of axial strain was reached.

Hydraulic conductivity tests were conducted on waste mixture specimens using a falling headwater-constant tailwater system. The schematic setup of the hydraulic conductivity test is shown in Fig. 3.3. The same specimens (50 mm x 100 mm) that were used for the CU tests were subjected to the hydraulic conductivity. These specimens were saturated following the same procedure used in the CU triaxial test. The head loss across the test specimen during permeation was measured and recorded. The volume of the effluent was also measured to calculate hydraulic conductivity. The hydraulic conductivity test continued until changes in hydraulic conductivity with time were negligible.

Table 3.2 Results of CU Triaxial test

	Sample ID	Confining pressure (kPa)	Dry density before curing (g/cm^3)	Dry density after curing (g/cm^3)	B value (-)	Peak deviator stress (kPa)	Axial strain (%)
Samples at initial condition	A1	50	1.02		0.95	242.6	15.0
	A2	100	1.02		0.95	276.8	14.9
	A3	150	1.02		0.95	320.3	14.9
Samples cured for 7 days	B1	50	1.02	-	-	360.2	8.0
	B2	100	1.02	-	0.95	388.9	5.6
	B3	150	1.02	-	0.96	411.1	8.0
Samples cured for 14 days	B4	50	1.02	1.02	0.95	329.5	10.1
	B5	100	1.03	1.03	0.95	393.9	15.0
	B6	150	1.02	-	0.94	429.2	8.3
Samples cured for 28 days	B7	50	1.02	-	0.98	373.4	12.0
	B8	100	1.03	-	0.96	427.9	10.1
	B9	150	1.02	-	0.95	438.6	13.7
Samples cured for 60 days	B10	50	1.02	1.03	0.95	357.8	14.8
	B11	100	1.02	1.04	0.95	416.5	8.0
	B12	150	1.02	-	0.97	444.3	9.6
Samples cured for 90 days	B13	50	1.02	1.09	0.95	401.6	15.0
	B14	100	1.02	1.03	0.95	448.8	15.0
	B15	150	1.02	1.09	0.95	485.5	15.0
Samples cured for 120 days	B16	50	1.02	1.02	0.97	355.5	15.0
	B17	100	1.03	1.03	0.98	458.0	7.2
	B18	150	1.02	1.03	0.95	486.0	7.2
Samples cured for 150 days	B19	50	1.02	1.04	0.96	410.5	8.1
	B20	100	1.02	1.06	0.95	500.3	14.4
	B21	150	1.02	1.17	0.97	630.6	10.2
Samples cured for 180 days	B22	50	1.02	1.26	0.95	493.9	10.7
	B23	100	1.02	1.05	0.95	546.3	11.6
	B24	150	1.02	1.10	0.95	612.5	5.3

Note: - Missing data

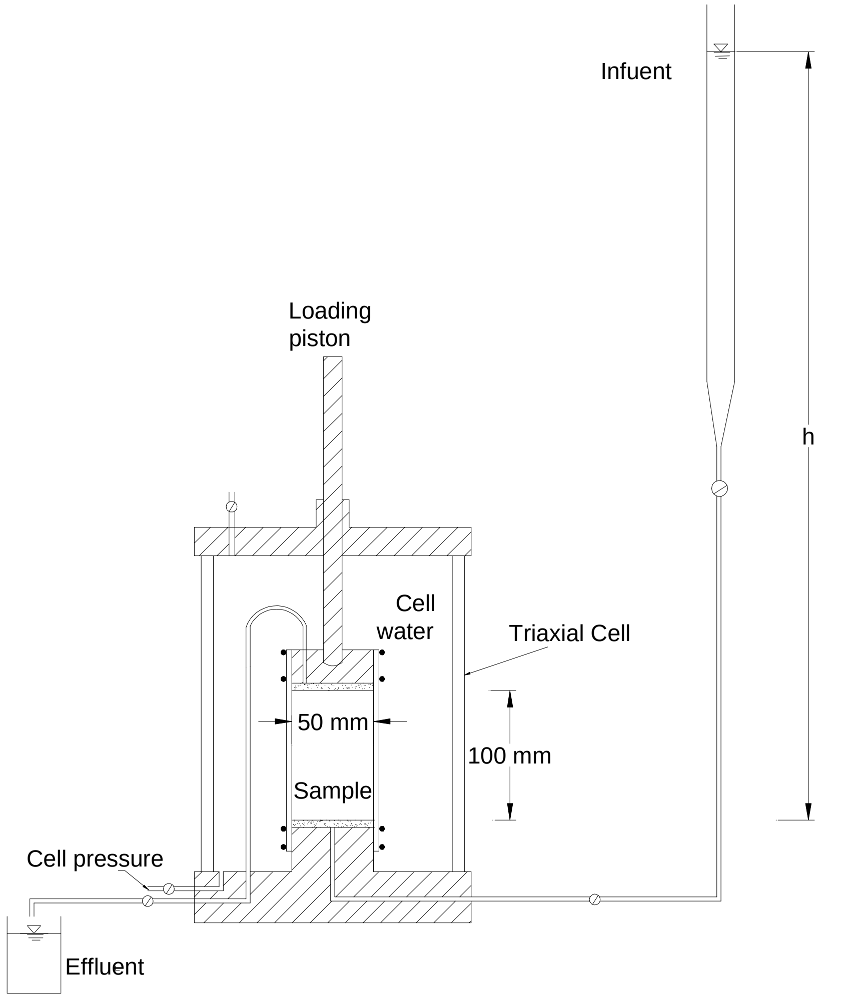


Fig. 3.3 Schematic setup of hydraulic conductivity tests in triaxial machine

3.2.2.2 XRD and Microscopic Analysis

The mineralogical content of the waste mixture samples were determined by a X-ray diffractometer (RAD-2B, Rigaku Corporation, using Cu target with a Ni filter and input energy of 40kV and 20 mA). After running CU triaxial test, samples were stored at a constant temperature of 30 ± 3^{o}C in an oven for 24 hour. Then, part of these samples was taken and grounded to powder with a particle size smaller than 75 μm. The resulting powder was analyzed with XRD. The angle scanned (2θ) ranged from 3 to 40°.

Fragments of 5 mm^2 from the samples that were used for the triaxial test, were dried at at 30 ± 0.1^{o}C in an oven for 24 hour. Then the SEM device (JSM-5510LV, JEOL) was used to observe the changes of microstructure. The SEM images were observed at a magnification of about 100-5000 to allow evidence of crystallization and other chemical reactions to be identified.

3.3 Results and discussions

3.3.1 CU tests

3.3.1.1 Stress-strain and pore pressure in CU tests

The CU test results are summarized in Table 3.2. Figures 3.4 to 3.6 show the stress-strain curves for samples cured in simulated leachate from 0 to 180 days. Generally, the deviator stress increases dramatically from 0 to 2 % of axial strain and reaches a peak after 6% of axial strain. After that, the deviator stress reaches an almost constant value until 15% of axial strain. The increase in strength of the waste mixture samples versus curing time was observed. For samples that sustained a low confining pressure (50 kPa), the peak deviator stress at initial conditions was about 250 kPa, while the peak deviator stress of samples cured in simulated leachate was in the range of 300 to 500 kPa. In the case of samples that sustained a higher confining pressure (150 kPa), the peak deviator stress under initial conditions was 300 kPa, while the peak deviator stress for samples cured in simulated leachate for 180 days increased to approximately 600 kPa, which was two times higher than that of samples at initial conditions. It can be observed that samples that were cured in simulated leachate showed a higher deviator stress compared to samples under initial conditions.

Figures 3.7 to 3.9 show the results of pore pressure versus axial strain. For the initial samples under 50 kPa confining pressure, the pore water pressure shows an increase trend at the initial stage until it reached a peak value (20kPa) and then it reduces steadily to about zero at 15% of axial strain. In contrast, pore water pressures increase and reach a peak at 2% and then keep a constant value until an axial strain of 15% is reached for initial samples under 100 and 150 kPa confining pressure. The samples under initial condition showed a contractive behavior in shearing process due to the positive value of the pore water pressure when the axial strain increased from 0 to 15 %.

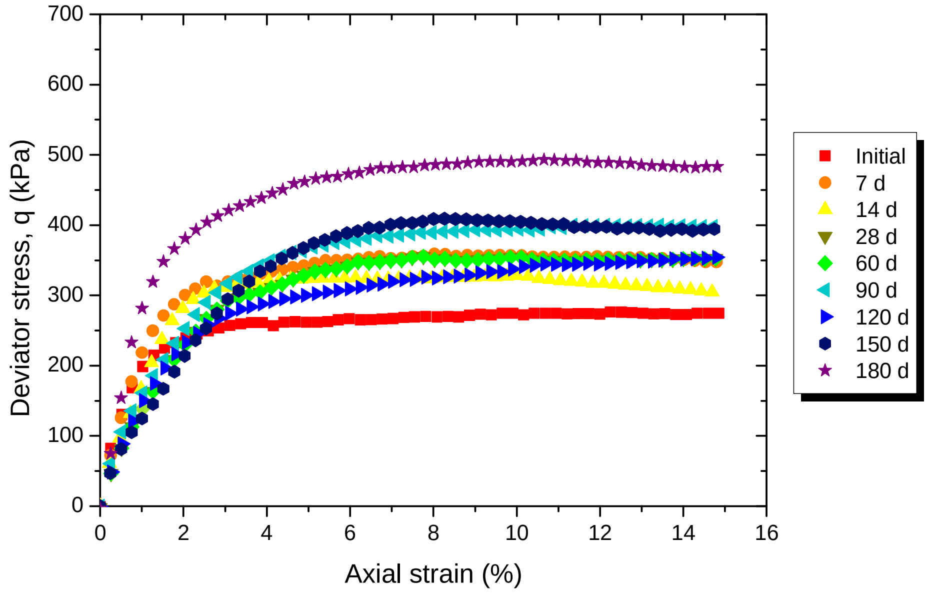


Fig. 3.4 Deviator stress versus axial strain for samples under 50 kPa confining pressure

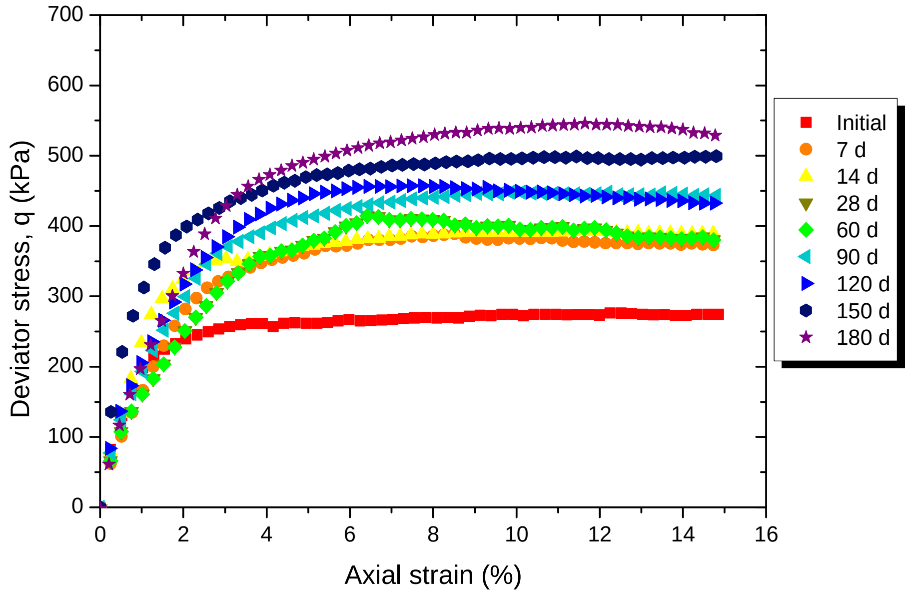


Fig. 3.5 Deviator stress versus axial strain for samples under 100 kPa confining pressure

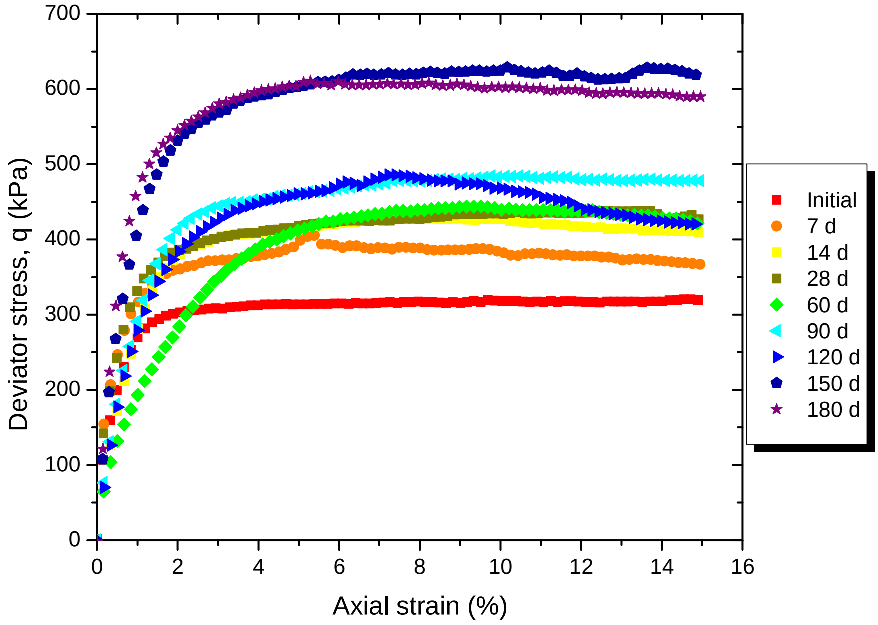


Fig. 3.6 Deviator stress versus axial strain for samples under 150 kPa confining pressure

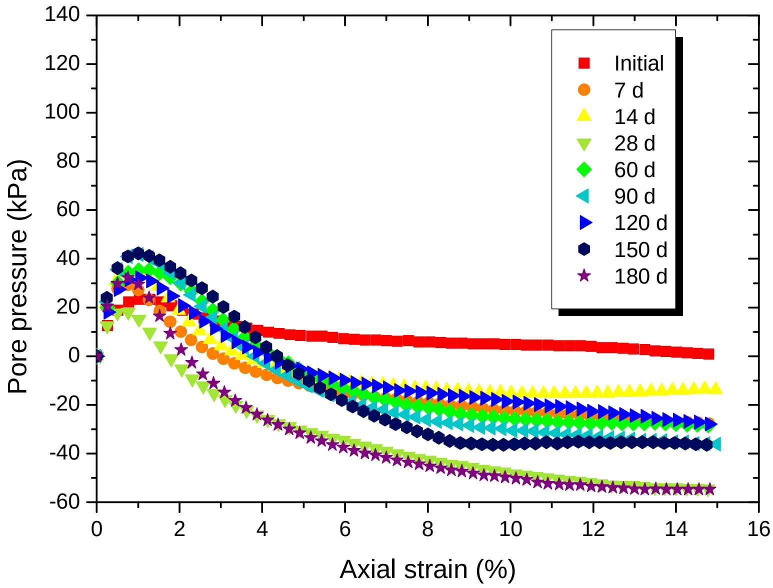


Fig. 3.7 Pore pressure versus axial strain for samples under 50 kPa confining pressure

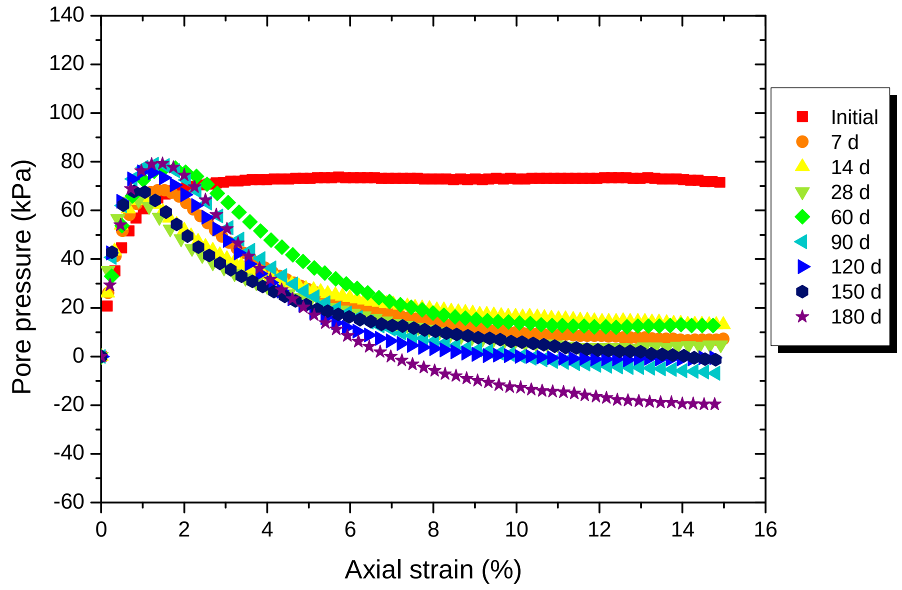


Fig. 3.8 Pore pressure versus axial strain for samples under 100 kPa confining pressure

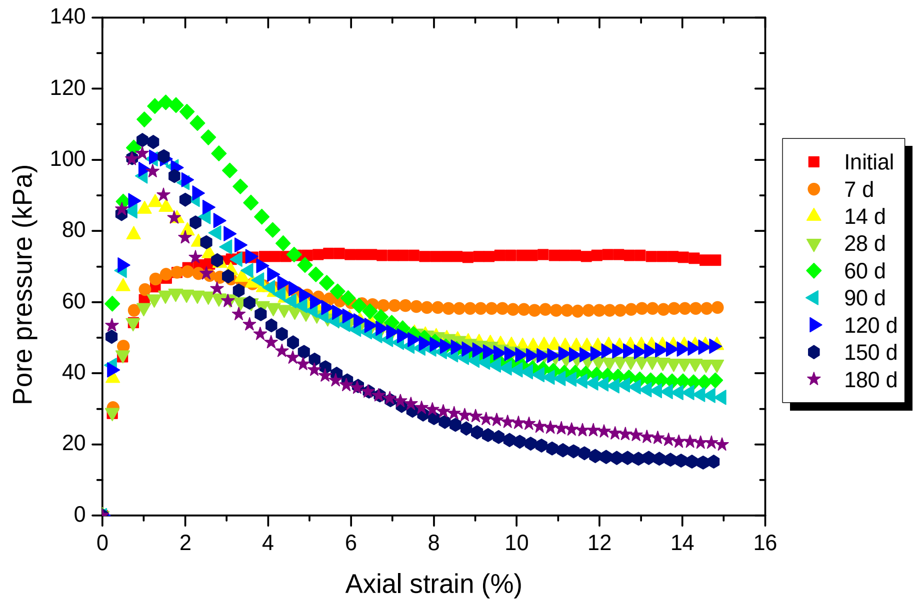


Fig. 3.9 Pore pressure versus axial strain for samples under 150 kPa confining pressure

Based on the experimental results, it was observed that the pore pressure increases with the raising of the confining pressure and curing periods. For samples that sustained 50 kPa of confining pressure, pore water pressure dramatically increased in the initial shear stage which indicates a contractive behavior. After reaching the peak value, at axial strains of about 1%, pore water pressure gradually decreased to a negative value for all the samples except those without curing. The peak pore water pressure was about 40 kPa and the largest negative pore pressure was approximately -60 kPa for samples cured in simulated water in the coastal landfill site for 180 days. The increased in the negative pore pressure showed an increased dilatancy behavior of waste mixture samples with curing time.

The pore water pressure results for samples that sustained 100 kPa of confining pressure are shown in Fig. 3.8. In this case, samples cured for 60, 90, 120, 150 and 180 days in simulated water in the coastal landfill site also show a dilatancy behavior due to the negative results of pore water pressure. The peak pore water pressure was about 80 kPa and the largest negative pore pressure was approximately -20 kPa for samples cured in simulated water in the coastal landfill site for 180 days. The positive value of pore pressure of samples that sustained 100 kPa confining pressure was twice the one obtained for samples under 50 kPa confining pressure, while the negative value of pore pressure of samples that sustained 100 kPa confining pressure was about one third of the one from samples under 50 kPa confining pressure.

In the case of specimens under an effective confining pressure of 150 kPa, all waste mixture samples showed positive values of pore-water pressure. The pore-water pressure increases to a peak at a small axial strain of about 1% and then starts dropping from its maximum value as the strain increases continuously. The initial buildup of positive pore-water pressure suggests that the specimens exhibit a contractive behavior. The reduction in the positive pore-water pressure after the peak indicates that the specimens change from contractive to dilative behavior during the shearing process. In fact, the pore water pressure of specimen for 7 days curing had similar behavior to the initial one. After 7 days curing, the waste mixture sample had a significant change in peak pore water pressure compare to initial one.

From the stress-strain and pore pressure in CU tests results, it is observed that the shear strength of the waste mixture samples increases with curing time due to change of pore water pressure. It is possible that the formation of hydration products fills the pores in the waste mixture fabric and this in turn affect the behavior of pore pressure. Thus, materials with denser structure show a higher dilatancy and that is related to the negative pore pressure that was generated during shearing process.

3.3.1.2 Stress-path

The deviator stress (q) and the mean effective stress (p') are calculated by following Eqs. (3.1) and (3.2):

$$q = (\sigma'_1 - \sigma'_3) \tag{3.1}$$

$$p' = (\sigma'_1 + 2\sigma'_3)/3 \tag{3.2}$$

where σ'_1 and σ'_3 are the effective axial and confining stress. The effective stress paths were plotted in a p'-q plane as it can be seen in Figs. 3.10 to 3.12. The stress paths showed a similar tendency. From the beginning, stress paths showed an increase of pore pressure with the stress path moving to the left until pore pressure reduces and the effective pressure increases moving the stress path into the right direction. In addition, the stress paths also showed an increase of shear strength with curing time. The stress paths values clearly increased with curing time.

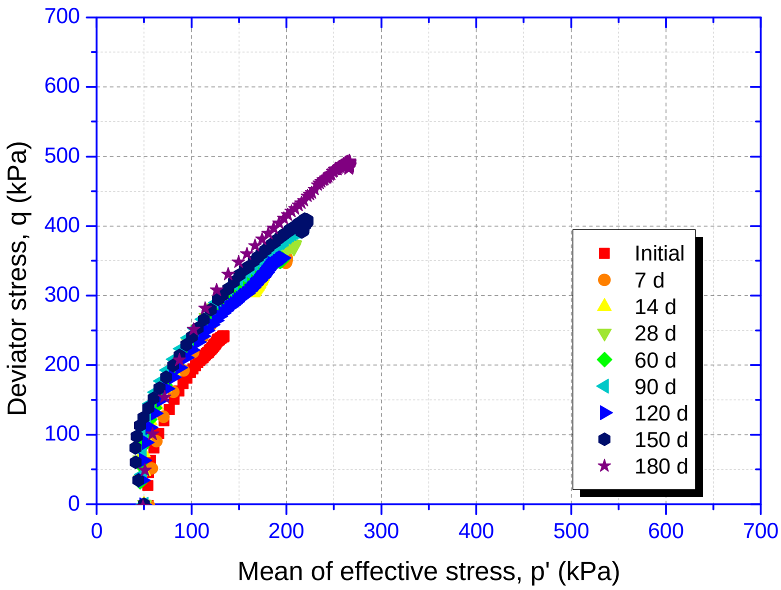


Fig. 3.10 Effective stress paths for samples under 50 kPa confining pressure

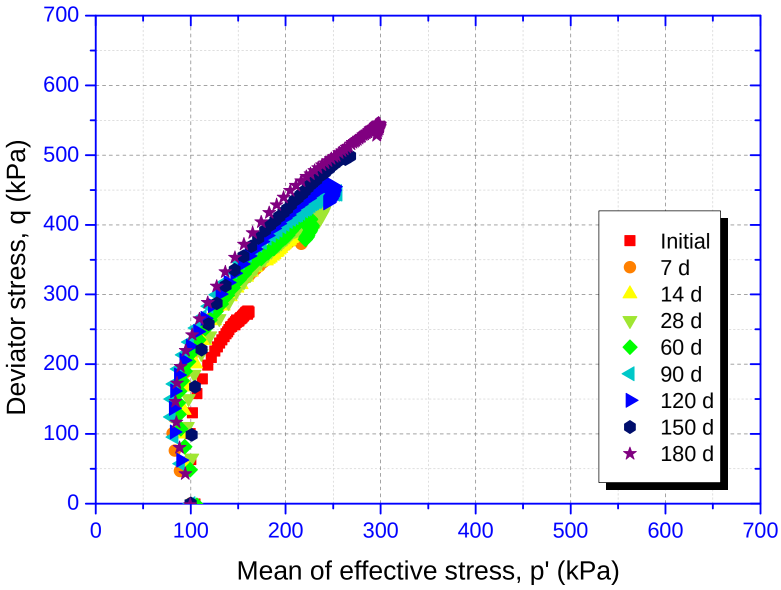


Fig. 3.11 Effective stress paths for samples under 100 kPa confining pressure

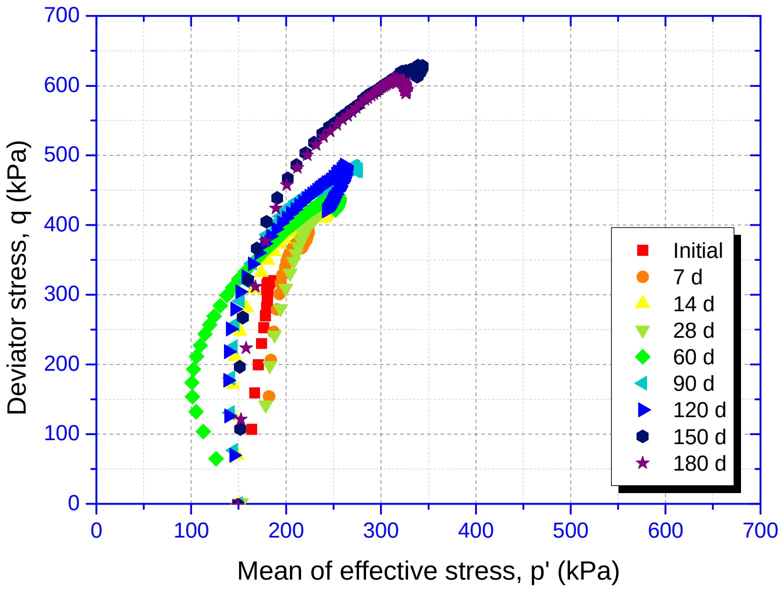


Fig. 3.12 Effective stress paths for samples under 150 kPa confining pressure

3.3.1.3 Critical state

Critical state soil behavior captures the large-strain behavior of soils in terms of *p*', *q* and void ratio *e*. The critical state line (CSL) is the loci of critical state conditions in the *e*-*p*'-*q* space (Roscoe et al. 1958). Its projection on the *p*'-*q* space defines the strength parameters as presented by:

$$M_{cs} = \frac{q_{cs}}{p'_{cs}} = \left(\frac{6\sin\phi_{cs}}{3 - \sin\phi_{cs}}\right) \tag{3.3}$$

where *CS* denote critical state. The second term applies to axisymmetric, axial compression, and it is a function of the constant volume critical state friction angle ϕ_{cs}.

In order to compare the shear strength under the same effective confining pressure (100kPa) at different effective stress path, the critical lines were drawn from the origin of the p'-q plane with different slopes according to M_{cs} (See Fig. 3.13). The critical state lines were plotted with M_{cs} = 1.8; 1.9; 2.1; 2.3; 2.4. It was observed that the effective stress path is shifted to the upper left. The M_{cs} for initial samples and samples cured for 7, 14, 28, 60, 90, 20, 150 and 180 days is 1.8; 1.9; 2.1-2.3; and 2.3-2.4, respectively. Therefore, the M_{cs} increased with curing time. It can be determined that the longer the curing period the greater the shear strength.

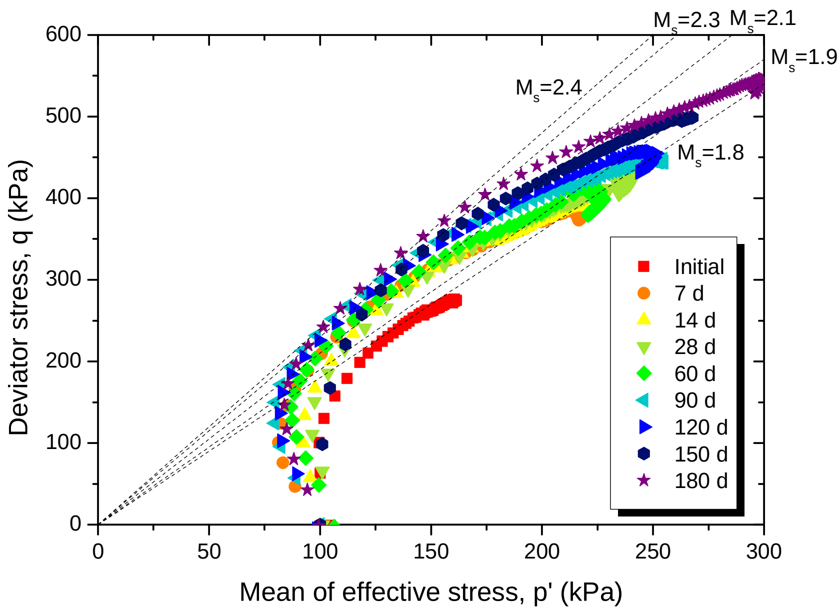


Fig. 3.13 Effective stress paths for waste mixture samples at 100 kPa confining pressure

3.3.1.4 Modulus of elasticity

The Modulus of Elasticity was obtained from the deviator stress-axial strain curve. This is a nonlinear curve (See Figs. 3.4 to 3.6). In this research, the Modulus of elasticity for waste mixture samples was calculated with the procedure which proposed by Kondner (1963). In Kondner model, the stress-strain curve can be represented by hyperbolic equations:

$$(\sigma'_1 - \sigma'_3) = \frac{\varepsilon}{a + b.\varepsilon} \tag{3.4}$$

This equation can also be written as:

$$\frac{\varepsilon}{\sigma'_1 - \sigma'_3} = a + b.\varepsilon \tag{3.5}$$

A plot of $\varepsilon/(\sigma'_1 - \sigma'_3)$ versus ε will be a straight line with a slope (b) and an intercept (a) with the ordinate. The modulus of elasticity of soil is given by the equation.

$$E = 1/a \tag{3.6}$$

For all the tests, the Modulus of elasticity varies between 25 and 65 MPa (Table 3.2). This modulus depends on the confining pressure and shows a similar behavior to dense sands. In the case of specimens under an effective confining pressure of 150 kPa, all waste mixture samples showed an increase of Modulus elasticity with curing time (See Fig. 3.14). In particular, the Modulus elasticity for samples cured for 180 days is about twice the value obtained for samples under initial condition.

Table 3.2 Modulus of elasticity

Curing period (days)	**Modulus of elasticity (MPa)**		
	σ’$_3$=50 kPa	**σ’$_3$=100 kPa**	**σ’$_3$=150 kPa**
0	25.8	28.3	32.2
7	39.2	37.7	40.6
14	32.4	41.0	42.7
28	40.2	43.5	44.5
60	39.0	42.4	47.2
90	44.3	48.8	50.1
120	39.0	46.7	44.8
150	45.9	52.3	64.4
180	52.3	60.4	60.6

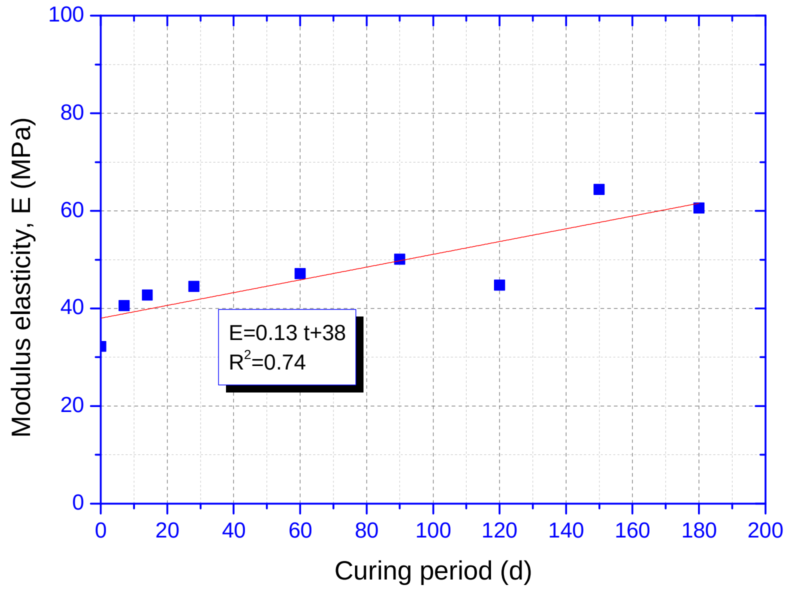


Fig. 3.14 Modulus of elasticity versus curing period for waste mixture samples under 150 kPa confining pressure

3.3.2 Hydraulic conductivity tests

The hydraulic conductivity (*k*) test results are presented in Table 3.3. As curing time increases, the hydraulic conductivity shows a decreasing trend. The *k* value of waste mixture samples decreases from 4.19 x 10^{-4} cm/s to 5.92 x 10^{-5} cm/s for samples at initial conditions and samples cured for 180 days, respectively. The range of *k* is similar to the *k* value for incinerated ash sample presented by Itoh et al. (2005).

Towhata et al (2010a) carried out a research study about incinerated ashes submerged in water that also showed a decrease trend in hydraulic conductivity where the generation of cement products reduced the pore structure of the samples. However, neither the cement generation processes nor the type of products generated were specified.

In this research, the decrease in hydraulic conductivity could be related to the reduction in pore structure in the waste mixture samples due to an increase of hydration products generated during the curing time as observed in XRD and SEM results mentioned later.

Table 3.3 Hydraulic conductivity test results

Curing period (days)	Hydraulic conductivity *k* (cm/s)
0	4.2×10^{-4}
7	3.6×10^{-4}
14	2.1×10^{-4}
28	4.6×10^{-4}
60	3.0×10^{-4}
90	3.0×10^{-4}
120	2.9×10^{-4}
150	2.7×10^{-4}
180	5.9×10^{-5}

3.3.3 X-ray Diffractograms

Figures 3.15 to 3.19 show the XRD results for initial samples and samples that were cured for 90, 150 and 180 days. As shown in Fig. 3.15, calcite, gypsum and quartz can be clearly observed in the samples under initial conditions. Calcite shows the highest intensity (580 cps; 2θ=29.4°). The peak of quart and gypsum are reduced dramatically for samples cured in simulated leachate. In simulated leachate, Cl^- and sulfate ions (SO_4^{2-}) show the highest concentration. The gypsum is produced if the calcium contained in the waste mixture samples react as described in Eq. (3.7).

$$Ca^{2+}(aq) + SO_4^{2-}(aq) + 2\,H_2O \rightarrow CaSO_4 \bullet 2H_2O \qquad (3.7)$$

After that, the waste mixture samples react with gypsum to form ettringite. Ettringite is the substance responsible for the strength of cement-based solidification agents, and it is represented by the following reaction formulas:

$$3CaO \cdot Al_2O_3 + 3CaSO_4 + 32H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \qquad (3.8)$$

$$4CaO \cdot Al_2O_3 \cdot Fe_2O_3 + 6CaSO_4 + 2Ca(OH)_2 + 62H_2O \rightarrow \qquad (3.9)$$
$$\rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O + 3CaO \cdot Fe_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$$

In this research, the largest peak of ettringite (2θ=9.2°) was observed in samples cured for 180 days. Previous research inferred that the formation of ettringite

($3CaO.Al_2O_3.3CaSO_4.32H_2O$) caused a significantly decrease in moisture content by combining large amount of water molecules in its crystals, leading to early strength development in stabilized soil (Kamon and Nontananandh 1990).

The hydration products are expected to contribute to the increase in shear strength of material. In this study, XRD peaks indicate the presence of cementing products such as calcium silicate hydrate, $CaO.SiO_2.H_2O$ (CSH) and $CaO.Al_2O_3.SiO_2.H_2O$ (CASH). Previous studies investigated the formation of cementing products (CaO-SiO_2-H_2O, CaO-Al_2O_3-H_2O) by XRD and SEM (Kamon and Nontananandh 1990; Rajasekaran et al. 1997; Rajasekaran 2005). These studies demonstrated that the strength of lime or cement stabilized soil is primarily governed by the formation of cementing products. Similarly, cements products can be seen in Fig. 3.16 to 3.19 with changes in pattern of XRD of waste mixture samples. As illustrated in these figures, XRD patterns of samples cured in seawater for 60, 90, 150, and 180 days showed several new peaks compared to the samples at initial conditions. These new XRD peaks indicate the presence of cementing products such as CSH peak at 2θ=31.3° and CASH peak at 2θ=15.8°. Previous research on stabilized soil also showed an increase in hydration products such as CSH and these products are the main reaction products that contribute to the strength development of stabilized soil. The strength increased in correspondence with X-ray intensities of CSH products (Ariizumi 1977; Kamon and Nontananandh 1990; Kamon et al. 2001).

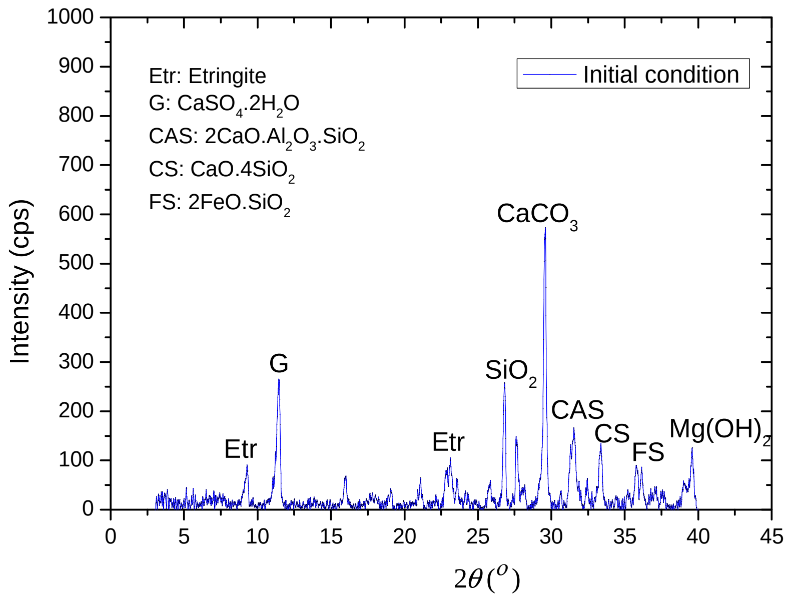


Fig. 3.15 XRD results of waste mixture samples under initial conditions

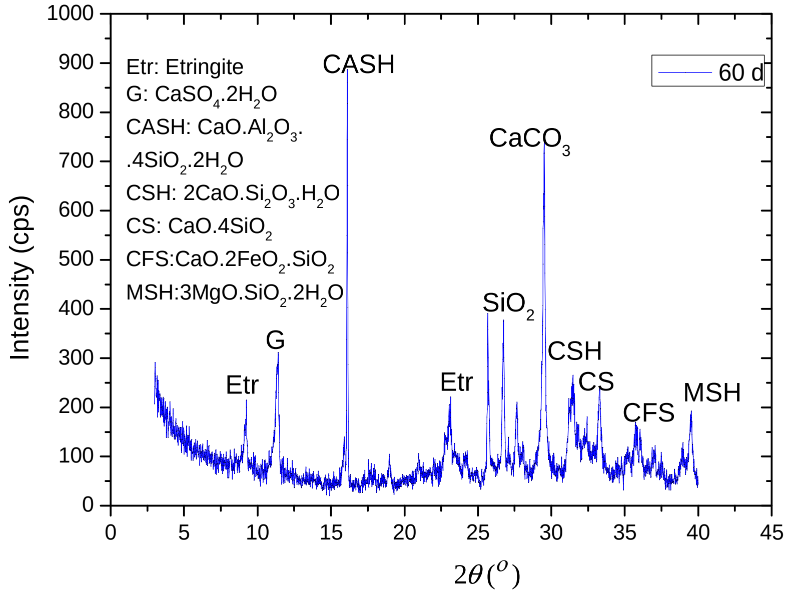


Fig. 3.16 XRD results for waste mixture samples cured for 60 days in simulated leachate

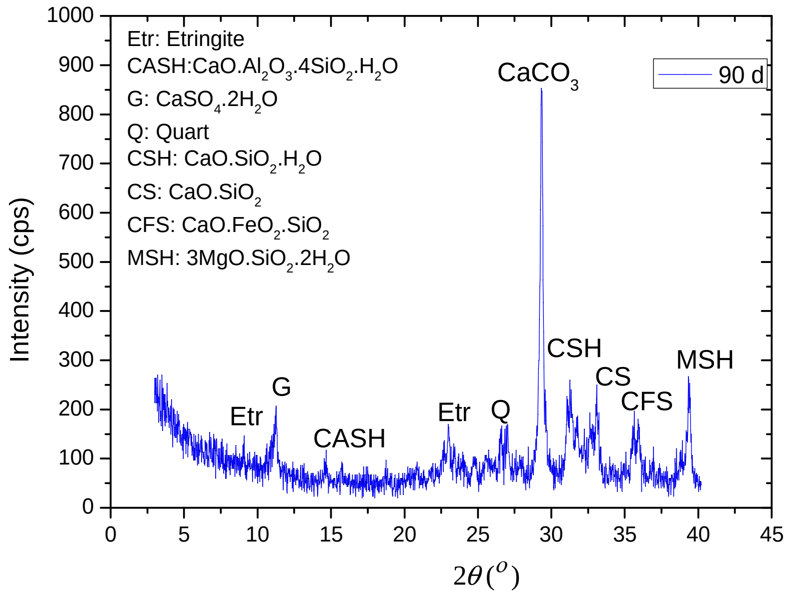


Fig. 3.17 XRD results for waste mixture samples cured for 90 days in simulated leachate

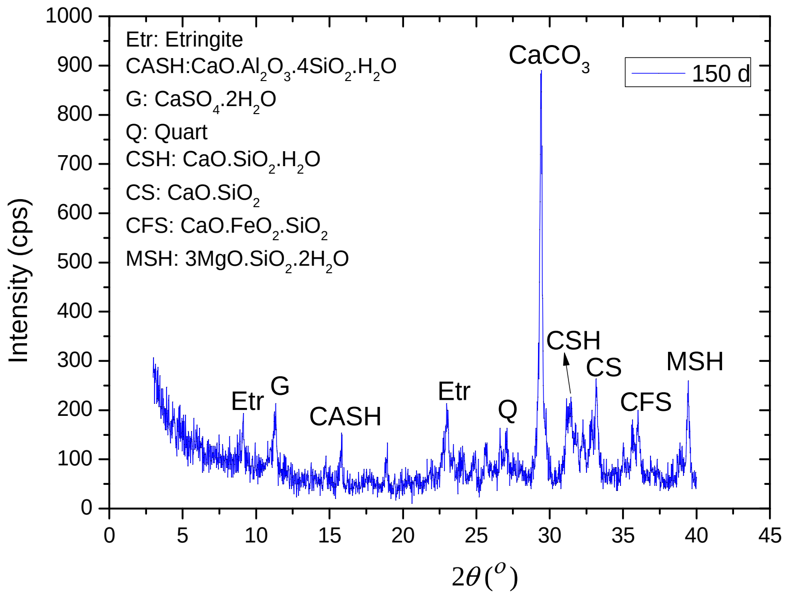


Fig. 3.18 XRD results for waste mixture samples cured for 150 days in simulated leachate

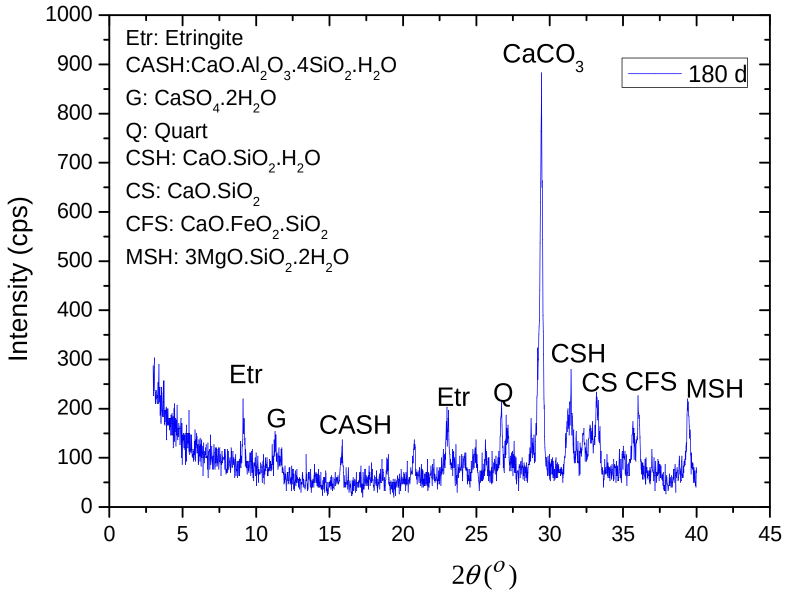


Fig. 3.19 XRD results for waste mixture samples cured for 180 days in simulated leachate

3.3.4 SEM image analysis

Figure 3.20 shows the microstructure of waste mixture samples under initial conditions. Based on the observation of the SEM micrograph, the surface of samples at initial conditions has numerous irregular particles.

The SEM images of samples that were cured in seawater for 60, 90, 150, and 180 days were shown in Figs. 3.21 to 3.24. There was no clear difference between the samples under initial conditions and samples that were cured for 60, 90, 150, and 180 days at 100-fold magnification. However, clear differences can be observed a 5000-fold magnification for samples under initial conditions and samples that were cured in simulated leachate. The presence of needle-like ettringite can be easily observed in samples that were cured for longer periods, more than in the initial samples. The presence of ettringite that fill up the voids in the waste mixture structure and at the same time, strengthen the connection between waste mixture particles. As a result, this action leads to an increase in the peak deviator stress and a reduction in hydraulic conductivity of the waste mixture samples.

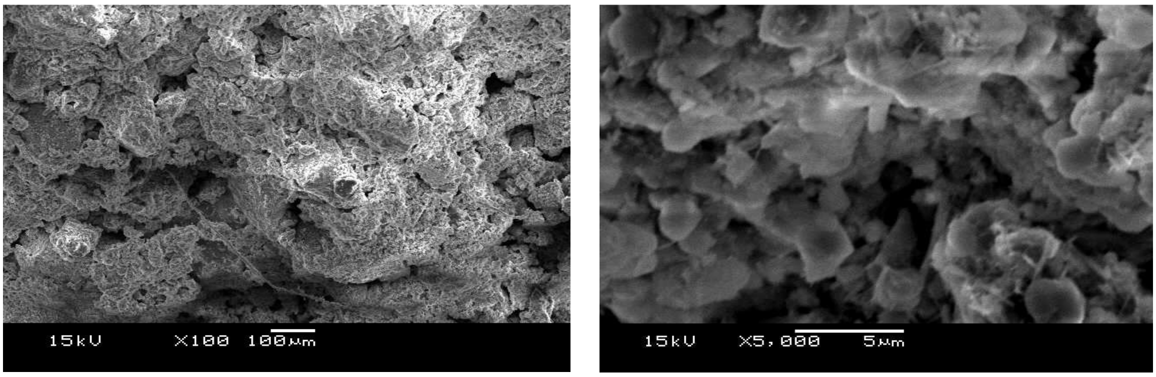


Fig. 3.20 SEM images for waste mixture under initial conditions

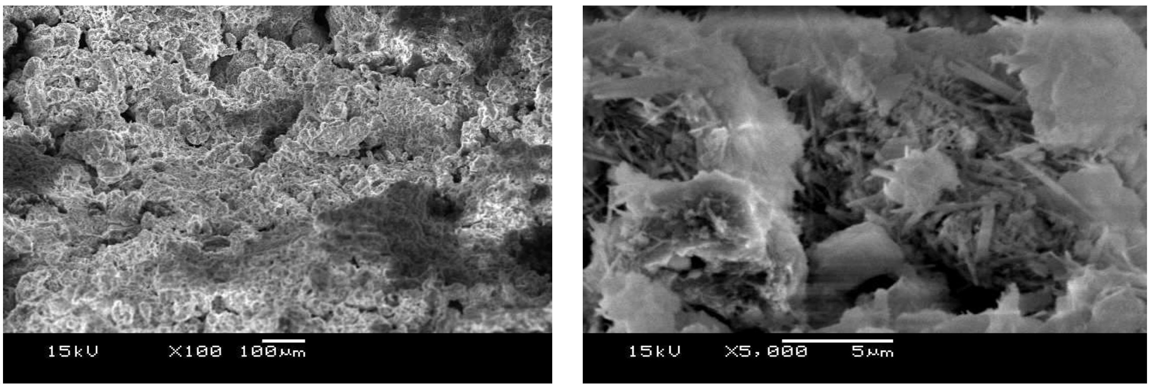


Fig. 3.21 SEM image of waste mixture samples cured for 60 days simulated leachate

.

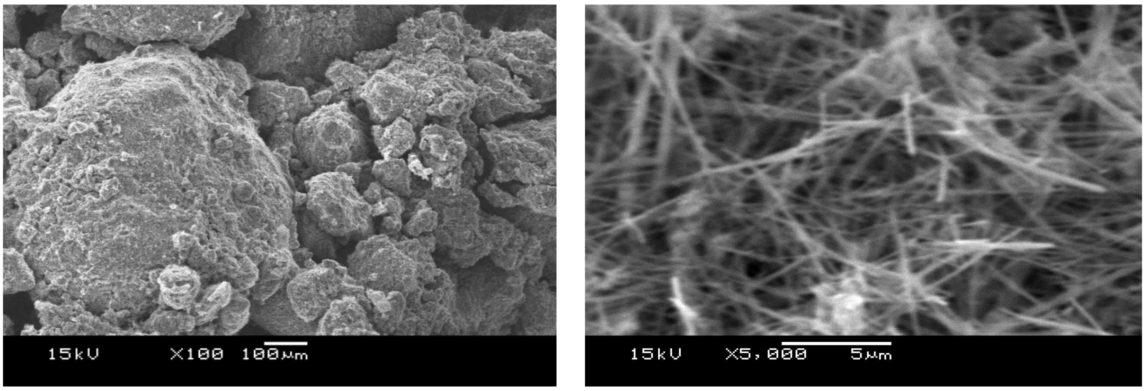


Fig. 3.22 SEM image of waste mixture samples cured for 90 days in simulated leachate

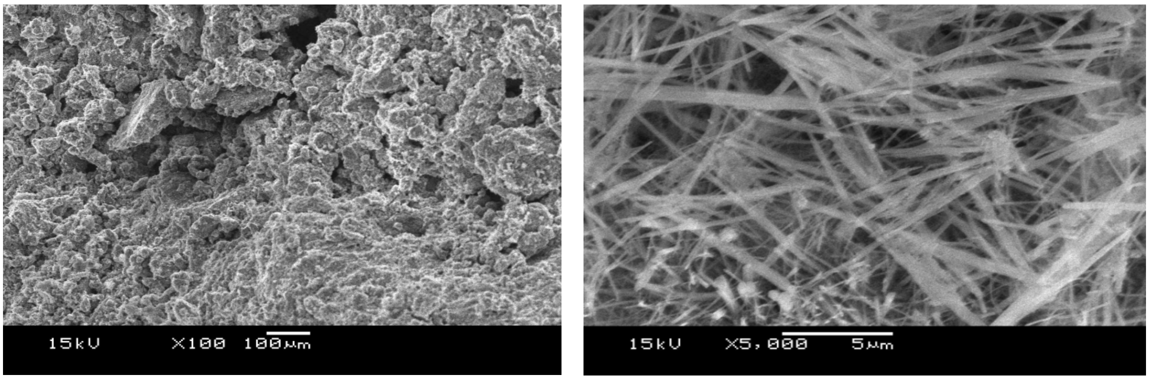


Fig. 3.23 SEM image of waste mixture samples cured for 150 days in simulated leachate

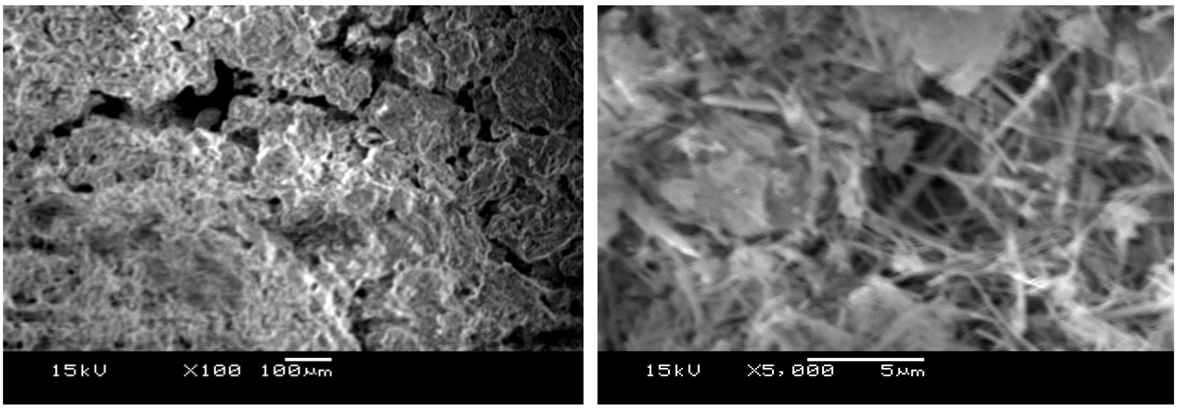


Fig. 3.24 SEM image of waste mixture samples after being cured for 180 days in simulated leachate

3.3.5 Effect of curing on mechanical properties of the waste mixture samples

The relation between peak deviator stress and mean effective stress for samples at different curing period is illustrated in Fig. 3.25. In order to estimate the shear strength parameters for all waste mixture samples, a linear interpolation have been used to determine them. The shear strength parameters are: 1) the cohesion intercepts *c*’ and 2) the angle of friction ϕ’. These parameters, associated with the linear interpolation, can be obtained using the following two equations:

$$\phi' = \sin^{-1}\left(\frac{3M}{6+M}\right) \tag{3.10}$$

$$c' = f\left[\frac{3-\sin(\phi')}{6\cos(\phi')}\right] \tag{3.11}$$

where *M* is the slope of peak strength envelope and *f* is the q-intercept of the peak strength envelopes in p’-q stress space.

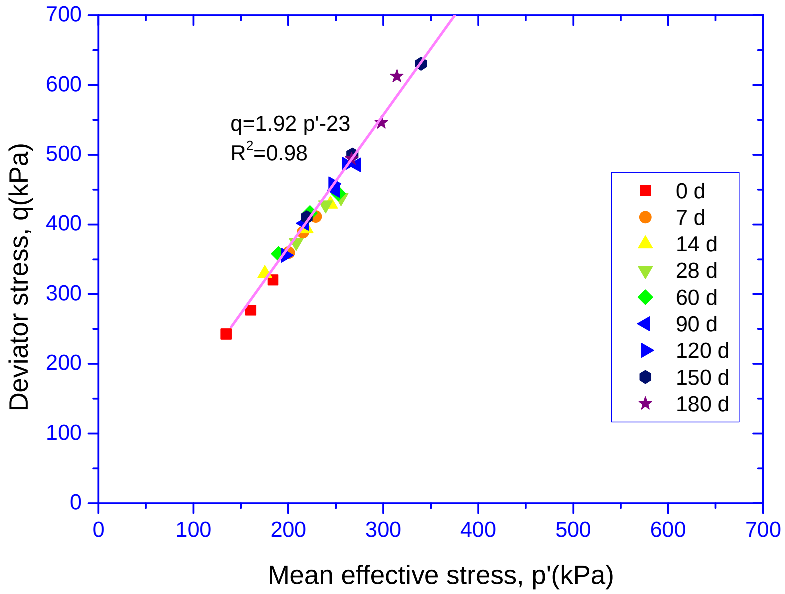


Fig. 3.25 Peak of deviator stress versus mean effective stress for samples at different curing periods.

In this figure, a unique behavior of peak deviator stress was observed. The peak strength envelope for all samples shows a small difference between slopes of peak strength envelope lines. It means that there is no significant change in friction angle and cohesion of specimen with curing period. The conceptual diagrams of waste mixture and simulated leachate interaction shown in Fig. 3.26 could be used to explain this behavior. When curing specimens, the interaction of waste mixture and simulated water in coastal landfill generated hydrations products and that in turn reduces the pore structure of samples. However, the waste mixture crystals and the hydration products are considered to have the same cohesion and friction angle and that lead to no changes in cohesion or friction angles in the specimen cured in simulated water in coastal landfill from 0 to 180 days. According to Mohr-Coulomb failure critical, the shear strength (τ_f) can be expressed in the following form:

$$\tau_f = c' + \sigma' \tan \phi' \tag{3.12}$$

where σ' is effective stress. The Eq. (12) indicated that the shear strength of sample include bond resistance and internal friction. But in this study, the cohesion and angle friction are kept constant. Thus the increase in shear strength of samples after being cured is not due to the bond effect or other effect to improve the shear strength properties of solid phase.

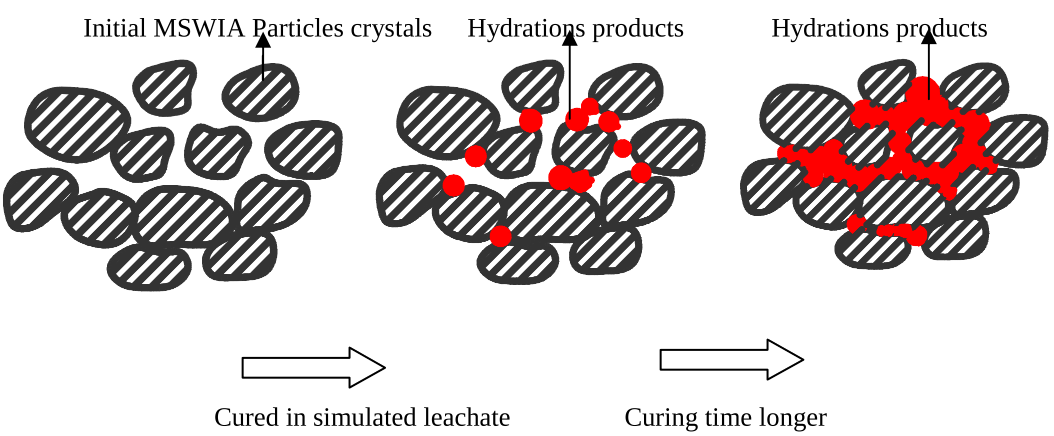


Fig. 3.26 Conceptual diagrams of waste mixture and simulated leachate interaction

The cohesion and friction angle obtained for the waste mixture samples are 0 kPa and 46.7°, respectively. Table 3.4 shows a summary of previous results by various researchers. It could be observed that the friction angle of the waste mixture samples in this research is larger than that one presented by Gotoh et al. (1998), Maeno et al.(1997) and Consoli et al. (2007) while it is smaller than results presented by Becquart et al. (2009). The difference of these friction angles could be related to the difference in density and resistance of angular particles as well as composition of samples. In the case of cohesion, the results present in this study are consistent with previous studies (Maeno et al. 1997; Consoli et al. 2007; Becquart et al. 2009).

Table 3.4 Summary results of various researchers

Curing period (days)	**c' (kPa)**	**ϕ' (°)**	***k* (cm/s)**	**Density (g/cm^3)**	**Type of waste mixture**	**References**
0	3.2	33.3	-	1.25	Bottom ash	Maeno et al. (1997)
0	0	37.2	1.1×10^{-2}	1.17	Municipal bottom ash	Gotoh et al. (1998)
0	0	41.3	2.6×10^{-3}	1.27		
0	-	-	1.0×10^{-5}	1.16	MSW incinerated ash	Doi et al. (2000)
180	-	-	1.0×10^{-8}	1.14		
0	12.7	44.7	-	-	Coal bottom ash	Consoli et al. (2007)
0	0	55.8	-	-	MSW incinerated bottom ash	Becquart et al. (2009)
0	0	46.7	4.2×10^{-4}	1.02	Waste mixture	This research
180			5.9×10^{-5}	1.1-1.2		

Note: - Not available
MSW: Municipal solid waste mixture

The relation between shear strength with curing time for samples under 150 kPa is shown in Fig. 3.27. The results showed that for samples that sustained 150 kPa of confining pressure and were cured in simulated leachate for 180 days, the shear strength is two times higher than the one for samples under initial conditions (i.e. 600 kPa against 300 kPa). The results can be attributed to the changes in pore water pressure and the changes in the structure of the material due to the generation of hydration products during the waste mixture and simulated leachate interaction. As previously discussed, the structure of the waste mixture is densified due to the pozzolanic reactions that cause the formation of hydration products (ettringite and CSH) and, in turn, reduce the sample's pore structure contributing to an increase in shear strength. The waste mixture samples that were cured in waste mixture and simulated leachate showed an increase in dry density that went from 1.02, after 14 days to 1.25, after 180 days (see Table 3.2). Therefore, the shear strength's improvement of the waste mixture samples with curing time is related to the changes in pore structure that contributed to a decrease in pore water pressure and; an increase in the dry density of the material. The XRD and SEM results support explaining the changes in pore structure of the waste mixture samples described above sections.

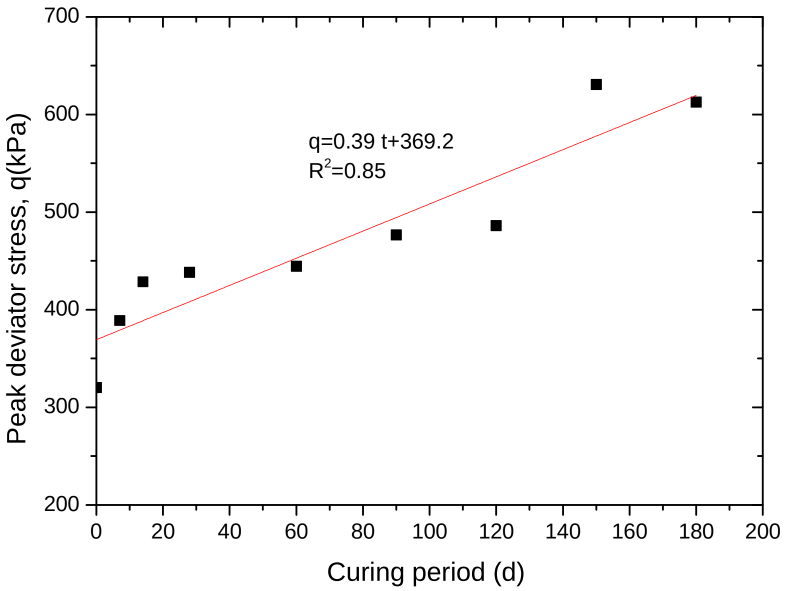


Fig. 3.27 Peak deviator stress versus curing period for waste mixture samples under 150 kPa confining pressure

The results of the XRD intensity for ettringite versus the peak deviator stress of waste mixture samples are plotted in Fig. 3.28. In this figure, the shear strength of waste mixture samples shows an incremental trend with an increase in XRD intensity of ettringite. A similar behavior, where shear strength increased due to ettringite formation, have been previously observed in stabilized soil by Kamon and Nontananandh (1990) and Kamon et al. (2001).

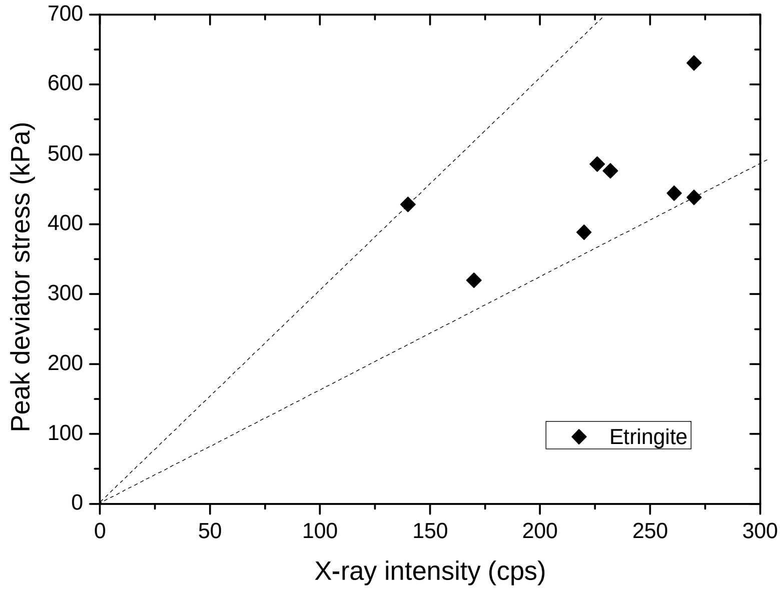
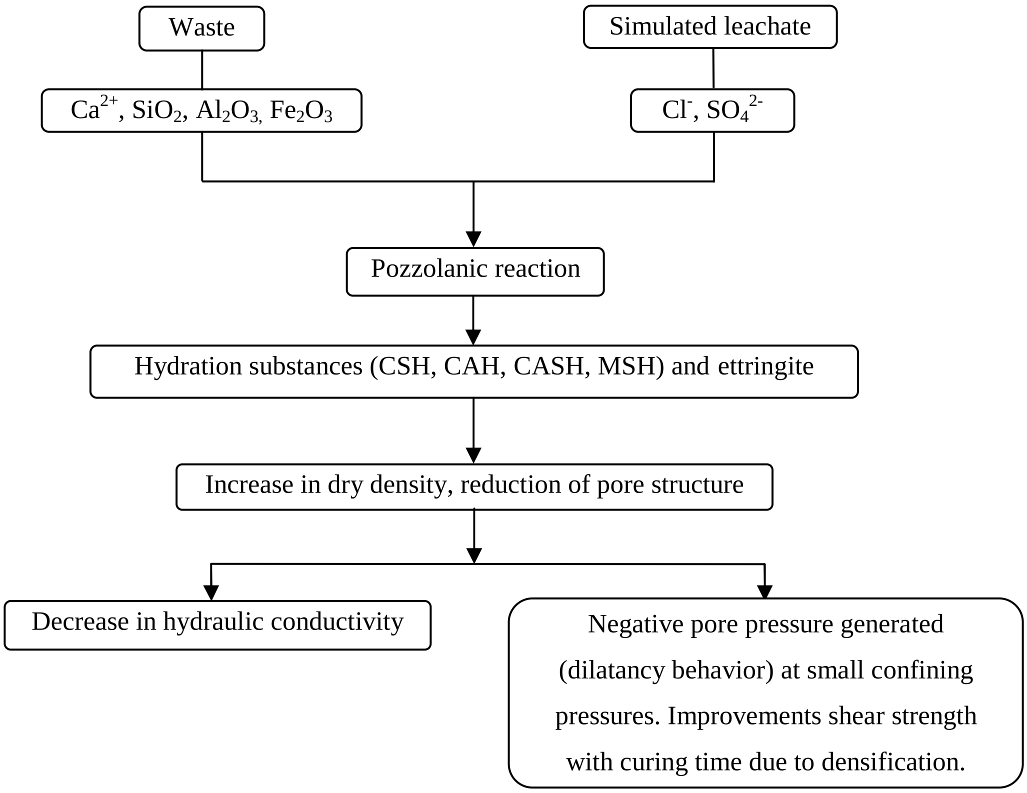


Fig. 3.28 Variation of peak deviator stress with XRD diffraction intensity of ettringite

From the test results, the hardening mechanism of waste mixture can be summarized in Fig.3.29. When waste mixture samples react with simulated leachate, Ca^{2+} reacts with SO_4^{2-} forming gypsum. Then, waste mixture samples react with gypsum to form ettringite. After that, the pozzolanic reactions take place generating hydration products such as CSH and ettringite. As a result, the pore structure of waste mixture is reduced by the generation of hydration products which filled the pore structure in the waste mixture samples as observed by the SEM and XRD analysis. Therefore, waste mixture samples become denser showing an increase in their dry density. The hydraulic conductivity of waste mixture samples is reduced. In the case of CU triaxial test, the densification of the waste mixture samples and the reduction of their pore structure lead to an increase the negative pore pressure during the shearing process due to the dilatancy effect. A higher dilative behavior was observed with longer curing periods. In addition, samples under low confining pressure showed a higher dilative behavior and a higher deviator stress with increases in curing time. It was observed an increase in shear strength in samples under low confining pressure compare to samples under higher confining pressures. Thus, the pore water pressure plays a major role in the increase of shear strength of waste mixture material.



Note: CHS: $CaO.SiO_2.H_2O$, CAH: $CaO.Al_2O_3.H_2O$, CASH: $CaO.Al_2O_3.4SiO_2.H_2O$, MSH: $3MgO.SiO_2.2H_2O$

Fig. 3.29 Mechanism of waste mixture and simulated leachate reaction

3.4 Summary

This study investigated the effects of waste mixture and simulated coastal landfill leachate interaction on the shear strength and hydraulic conductivity of the waste mixture layer in order to utilize a coastal landfill site after closure. The main components of the waste mixture layer are incinerator ash, slag and soil. The experimental results obtained are summarized below:

1) Waste mixture samples were submerged in simulated leachate and cured in maximum 180 days. The initial and cured samples were subjected to the test for mechanical properties. The results show that the shear strength and dilatancy of waste mixture samples increased with curing time. However, cohesion and friction angle do not change with curing period. Thus, an important finding is that the increase in shear strength with curing time is not due to cementation or bonding effects but only to densifications of waste mixture samples due to hydration. The mechanism of this behavior is that the structure of the waste mixture is densified due to the pozzolanic reactions when the waste mixture samples were submerged in simulated leachate that causes the formation of hydration products (ettringite and CSH). Moreover, the waste mixture crystals and the hydration products are considered to have the same cohesion and friction angle and that lead to no changes in cohesion or friction angles in the specimen cured in simulated leachate in coastal landfills. In addition, the trend of pore water pressure generated was that initial peak pore water pressure increased as curing time increased and final pore water pressure decreased. The larger curing period, the higher density and an increase in dilatancy of waste mixture samples are. It was also found that the effect of dilatant behavior is higher in samples under small confining pressure than in samples under high confining pressure. The pore water pressure contributed to the increase in stress paths and strength of waste mixture samples as increased curing time.
2) The results from the SEM and XRD analysis showed an increase in the formation of ettringite and other hydration products, such as CSH, with curing time. This behavior may be related to the formation of these products that decreased in pore structure of waste mixture samples. The SEM and XRD also confirmed the mechanism of curing waste mixture in coastal landfill sites.
3) Waste mixture samples showed an increase in the modulus of elasticity with curing time. This trend is consistent with the increase of shear strength of waste mixture samples. Therefore, waste mixture layer in this study could be used for construction due to its have adequate bearing capacity.

CHAPTER 4: SCALE EFFECTS ON THE SHEAR STRENGTH OF WASTE MIXTURE IN COASTAL LANDFILL SITES

4.1 General Remarks

In Japan, a significant volume of municipal solid waste incinerator ash (MSWIA), slag and soil are disposed in coastal landfill sites located in Tokyo and Osaka bay. Future reclamation of these final disposal sites is an important goal. Thus, it is relevant to understand the strength and deformation properties of the waste mixture layers in coastal landfill sites to utilize the land after closure. However, the particle size distribution of the waste mixture ranges from fine-grained to coarse-grained (gravel, glass, etc.) affecting the estimation of the geotechnical properties of the waste mixture sample in coastal landfill sites.

The stress-strain behavior of a sample material is normally investigated by a triaxial test. When triaxial tests are run, the maximum particle size of the samples must be less than one-sixth of the diameter of the specimen. Therefore the standard triaxial test, with a specimen of 50 mm in diameter, cannot be used if the diameter of the waste mixture sample is larger than 9.5 mm. In this research, large-scale and small-scale triaxial tests were carried out on waste mixture samples to study the effect of specimen size on the shear strength of the samples. This chapter deals with the effects of particle size and confining pressure on the shear strength of waste mixture samples.

4.2 Background

Triaxial testing is widely used to evaluate the shear strength and mechanical behavior of geomaterials. Limitations arise from the size of the triaxial apparatus and the maximum particle size (d_{max}) of the materials to be tested.

Numerous research studies have attempted to increase the maximum particle size of the specimens tested by increasing the size of the testing apparatus in order to accurately measured the mechanical behavior of geomaterials (Hennes 1952; Holtz and J. 1956). Various tests and results related to large scale experiments are summarized in Table 4.1.

Table 4.1 Summary of the scale effect for different materials

Type of test	Type of material	Dimension of specimen	Comments	Source
Large direct shear test	Rounded gravel and crushed rock	152.4 mm x 304.8 mm	ϕ increase with d_{max} increased	Hennes (1952)
	Dense sand	-	ϕ reduce with increased box size	Cerato and Leteggee (2006)
	Sand and gravel	-	Increase gravel caused an increase in peak and constant volume friction angles	Simoni and Houlsby (2006)
	Sand with uniform particle size	-	ϕ reduce as mean particle size increase	Kirkpatrick (1965)
Large triaxial test	River sand and gravel	228.6 mm x 571.5 mm	ϕ increase with increase gravel content	Holtz and Gibbs (1956)
	Decomposed granite soils and river soil	100 mm x 200 mm	Undrained strength increase with increase C_u	Kokusho (2004)

Note: - unknown

d_{max}: Maximum diameter of material

Previous studies have investigated the effect of larged particles on shear strength of soil by using large triaxial test and reported that the increase in gravel content decreases the density and shear strength of the material (Fragaszy et al. 1990; Fragaszy et al. 1992). Kirkpatrick (1965) studied the Leighton Buzzard sand with uniform particle sizes using triaxial tests; the results showed a reduction in friction angle as the mean particle size increased while the porosity was kept constant. However, other researchers concluded that the shear strength of mixture (soil and gravel) increases with gravel content (Vallejo 2001; Yagiz 2001; Kokusho et al. 2004; Simoni and Houlsby 2006). For example, three kinds of particle gradation; RS1, RS2, and RS3 for the river soils and DGS1, DGS2, and DGS3 for the decomposed granite have been studied by cyclic and monotonic loading triaxial tests to investigate the effect of the particle gradation on the undrained shear characteristics (Kokusho et al. 2004). The stress paths of the decomposed soils and river soils are presented in Fig. 4.1 and 4.2. A comparison of the two figures reveals that in the soils of higher C_u (DGS2 and DGS3), the pore pressure cannot develop negative values as in the river soils samples (RS2 and RS3) that have lower Cu and suddenly turns to the reverse direction resulting in smaller undrained shear strength. This is probably caused by the crushability of the decomposed granite soils in which the contact between coarser grains is too weak to bear strong pore pressure and therefore dilative environment.

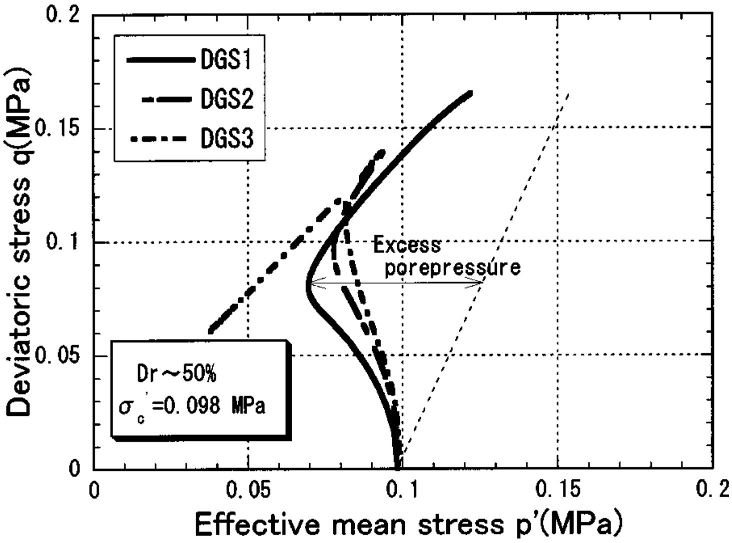


Fig. 4.1 Effective stress path obtained in undrained monotonic loading tests for decomposed soil (Kokusho et al. 2004)

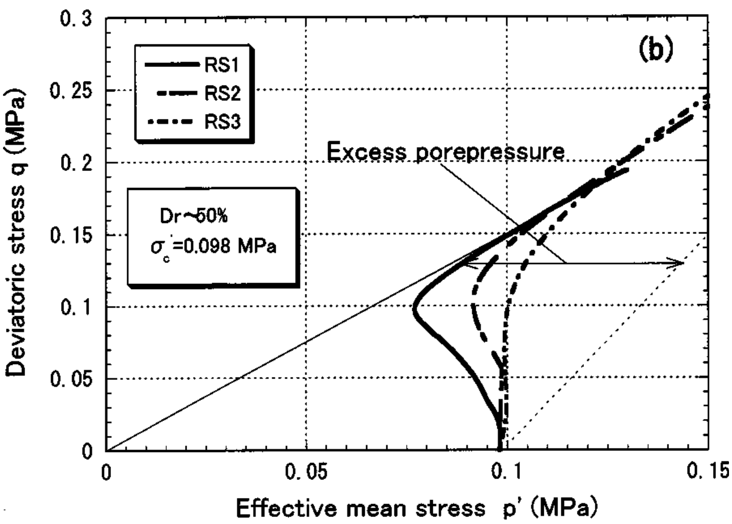


Fig. 4.2 Effective stress path obtained in undrained monotonic loading tests for river soil (Kokusho et al. 2004)

Direct shear test is another method that can be utilized to determine the shear strength. Hennes (1952) and Simoni and Houlsby (2006) utilized this method to test sand and gravel samples; the results showed that the addition of gravel to the mixture causes an increase in friction angle. However, Cerato and Lutenegger (2006) studied the scale effect of direct shear tests on sands and observed a decreased in friction angle when the maximum particle size increased. Their study showed that the friction angle measured by direct shear testing depends on sample size and that the influence of sample size is also a function of sand type and relative density. They concluded that for dense sand, the friction angle measured by direct shear tests is reduced as the box size increases at a ratio of at least 1:50 between box width and particle size.

There is no available research on the effects of large particle on the shear strength of waste mixture samples in coastal landfill sites. Therefore, this chapter presents the results of larger triaxial test (150 mm x 300 mm) for waste mixture samples.

4.3 Materials and methods

4.3.1 Materials

The waste mixture utilize for the experimental work in this study was obtained from the coastal landfill site in Osaka Prefecture. A sample of approximately 200 kg of wet waste mixture was collected before being disposed at the coastal landfill site. The waste mixture sample is mainly composed by incinerator ash, slag and surplus soil, etc. One the sample was bought to the laboratory; it was then dried in a room with an average temperature of $20^{o}C \pm 1\ ^{o}C$. After that, large pieces, such as glasses or rocks, were removed and the sample was sieved with a 9.5mm opening sieve and set aside until use for small triaxial test. In the case of samples for large triaxial test, particle size includes particles with a diameter $\leq$19 mm. Figure 4.3 shows the particle size distribution of the waste mixture sample, determined according to JIS A1204 for small and large samples. The material was well graded with a particle size distribution similar to SG-F (sand gravely with fine particle) following the JGS 0051. The specific gravity of the sample was 2.67

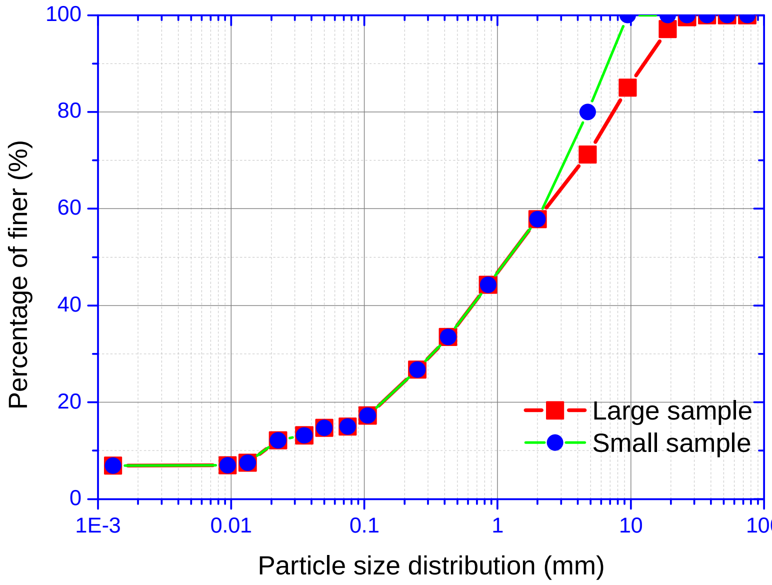


Fig. 4.3 Particle size distribution of waste mixture samples for small and large triaxial tests

a) D_{max}=9.5 mm (for small triaxial test)   b) D_{max}=19 mm (for large triaxial test)

Fig. 4.4 Particle size of waste mixture sample for small and large triaxial test

The maximum diameter of waste mixture for small and large triaxial test is 9.5mm and 19 mm, respectively (see Fig. 4.3). Pictures of samples used for both test can be observed in Fig. 4.4.

4.3.2 Methods

For large CU triaxial test, specimens were prepared by compacting 5 layers of waste mixture in to a split cylindrical mold (150 mm diameter and 300 mm in height) 0.8

times of maximum dry density (1.28 g/cm^3) with optimum water content of 34.5% according to the value obtained from the Standard Proctor Compaction Test (Fig. 4.5).

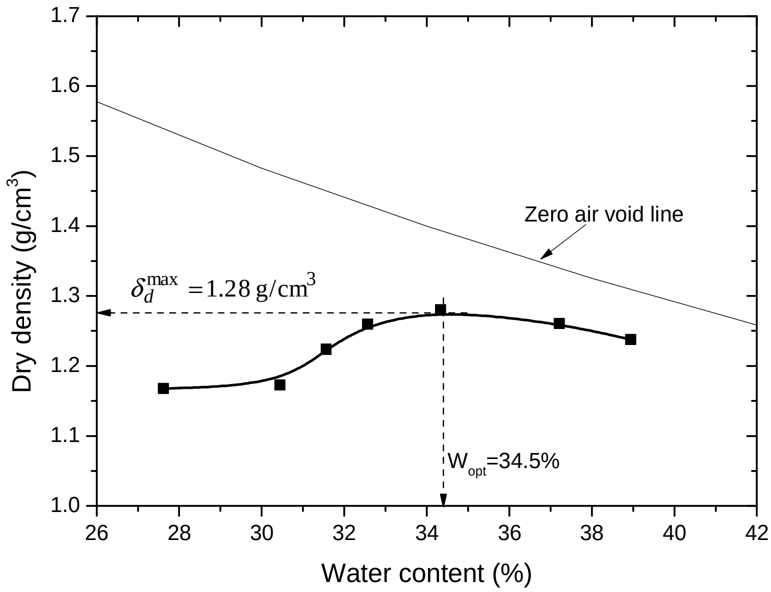


Fig. 4.5 Compaction curve for waste mixture samples

In this test, D/d_{max}= 15/1.9= 7.89 (where D is diameter of specimen in large triaxial test and d_{max} is the maximum particle size of waste mixture). For small CU test, the same procedure and tests were conducted as described in Chapter 3. The small CU test conducted on small samples (50 mm x 100 mm) as given in Chapter 3. The target of conducting small and large samples in triaxial test is to consider the effect specimen size on shear strength of waste mixture is considered. It is crucial to estimate the shear strength of waste mixture in coastal landfill sites for future land utilization. The initial conditions for large and small triaxial test are shown in Table 4.2.

Table 4.2 Initial condition of waste mixture samples

Type of Triaxial test	Confining pressure (kPa)	Dry density after consolidated (g/cm^3)	Void ratio e (after consolidated)	B value	D_{max} (mm)
For small triaxial test	50	1.02	1.62	0.95	9.5
	100	1.02	1.62	0.95	
	150	1.02	1.62	0.95	
For large triaxial test	50	1.02	1.61	0.95	19
	100	1.03	1.56	0.95	
	150	1.06	1.53	0.95	

Small and large CU triaxial tests were carried out on waste mixture specimens following the same procedure. These specimens were saturated by applying a vacuum procedure (Rad and Clough 1984) to keep a constant confining pressure of 20 kPa. After reaching the final step (-70 kPa for cell pressure and -90 kPa for sample pressure) de-aired water was circulated into the specimen for 3 hours and then sample pressure and cell pressure were reduced to -20 kPa and 0 kPa respectively. Back pressure was increased step by step until it reached 240 kPa and cell pressure was 220 kPa. After that, pore pressure coefficient (B-value) was checked to have B-values larger than 0.95 and ensure that samples were fully saturated. The samples were consolidated with an effective confining pressure of 50, 100 and 150 kPa and sheared at a constant strain rate of 0.5%/min until 15% of axial strain was reached.

4.4 Results and discussions

4.4.1 CU test for large triaxial test

Figure 4.6 shows the stress-strain curves for large samples. The deviator stress increases dramatically from origin to reach a peak value at about 2% of axial strain. After that, the deviator stress decreases steadily until 15% of axial strain and the stress-strain curves illustrate the strain softening behavior of waste mixture samples. This behavior significantly change compare with the results for small samples.

Figure 4.7 shows the pore water pressure versus axial strain. For specimens that sustained 100 and 150 kPa of confining pressure, the pore water pressure increases dramatically from 0% to 2% of axial strain and from 2% to 15% it has a mild but steady increases. In the case of specimen that sustained 50 kPa of confining pressure, pore water pressure has a constant value from 2% to about 15% axial strain.

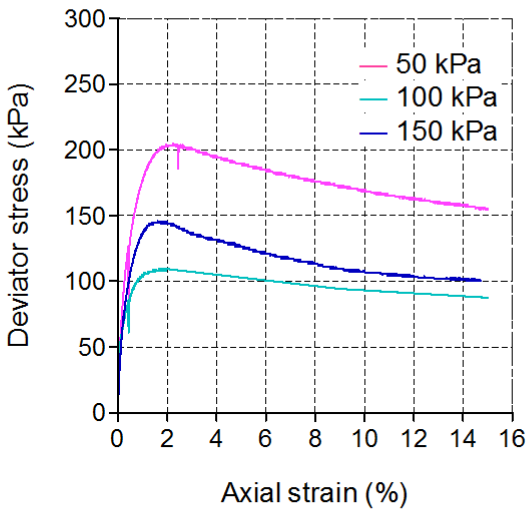


Fig. 4.6 Stress-strain curves for large samples

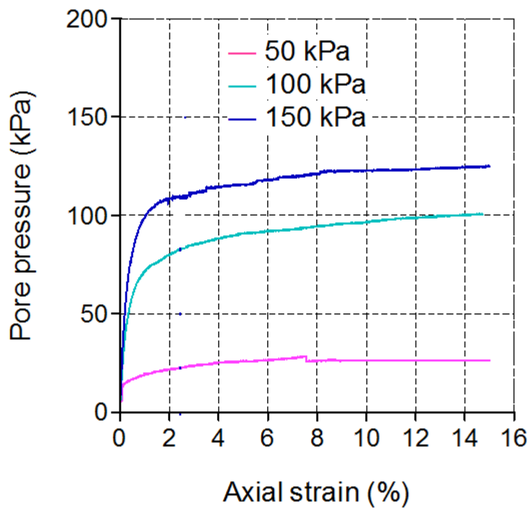


Fig. 4.7 Pore pressure results versus axial strain for large triaxial test

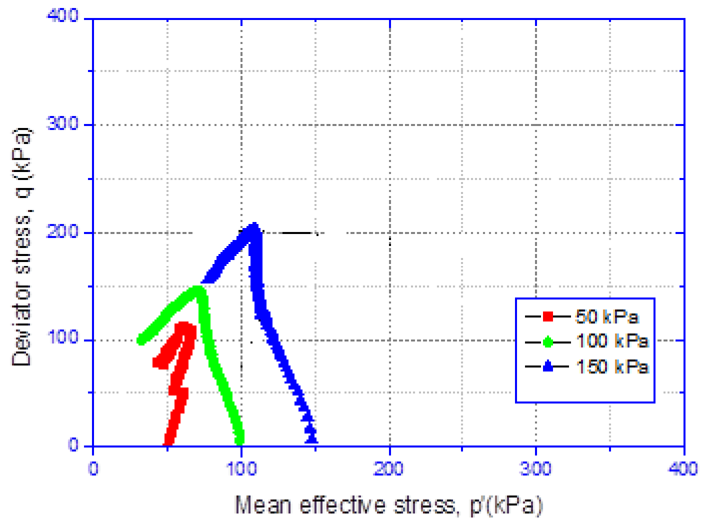


Fig. 4.8 Stress paths for large triaxial test

The deviator stress (q) and the mean effective stress (p') are calculated by following Eqs. (5.1) and (5.2):

$$q = (\sigma'_1 - \sigma'_3 \tag{4.1}$$

$$p' = (\sigma'_1 + 2\sigma'_3)/3 \tag{4.2}$$

where σ'_1 and σ'_3 are the effective axial and confining stress. Fig. 4.8 shows the effective stress paths were plotted in a p'-q plane. In this figure it can be observed that from the beginning, stress paths moves to the right until the deviator stress reach a peak value and after that the deviator stress starts decreasing due to an increase in pore water pressure.

4.4.2 CU test for small triaxial test

Figure 4.9 shows the stress-strain curves for small samples. Generally, the deviator stress increases dramatically from 0 to 2 % of axial strain and reaches a peak after 6% of axial strain. After that the deviator stress reaches a constant value until 15% of axial strain. The stress-strain curves illustrate the strain hardening behavior of waste mixture samples.

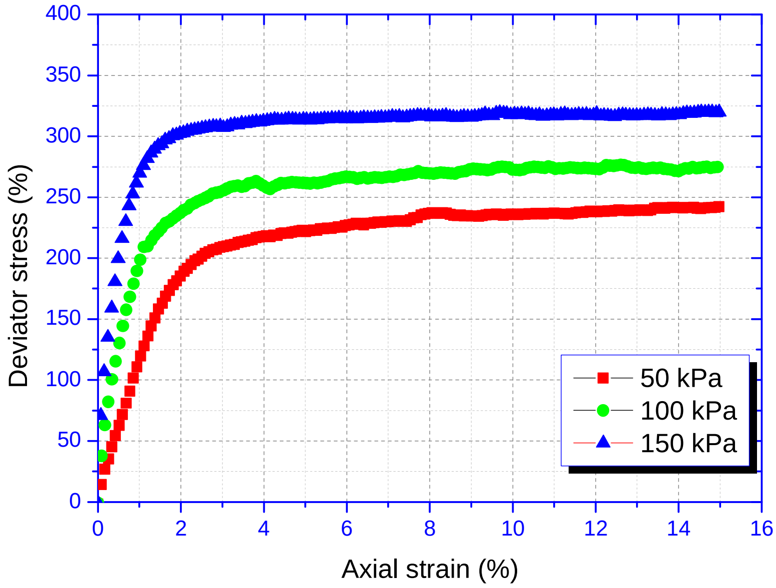


Fig. 4.9 Stress-strain curves for small samples

Figure 4.10 shows the pore pressure results versus axial strain. For samples under a confining pressure of 50 kPa, the pore water pressure shows an increase trend at the initial stage until it reached a peak value of about 20kPa and then it is reduced steadily to nearly zero at 15% of axial strain. Pore water pressure generated in samples that sustained 100 kPa confining pressure, showed a similar trend than samples under 50 kPa but reaching a pore pressure peak value of about 50 kPa and then reducing steadily until reaching about 35 kPa. However, for samples under 150 kPa, pore water pressure increases and reaches a peak at 2% and then keeps a constant value until an axial strain of 15% is reached. The samples under initial conditions in small triaxial test showed a contractive behavior in shearing process due to the positive value of the pore water pressure when the axial strain increased from 0 to 15 %.

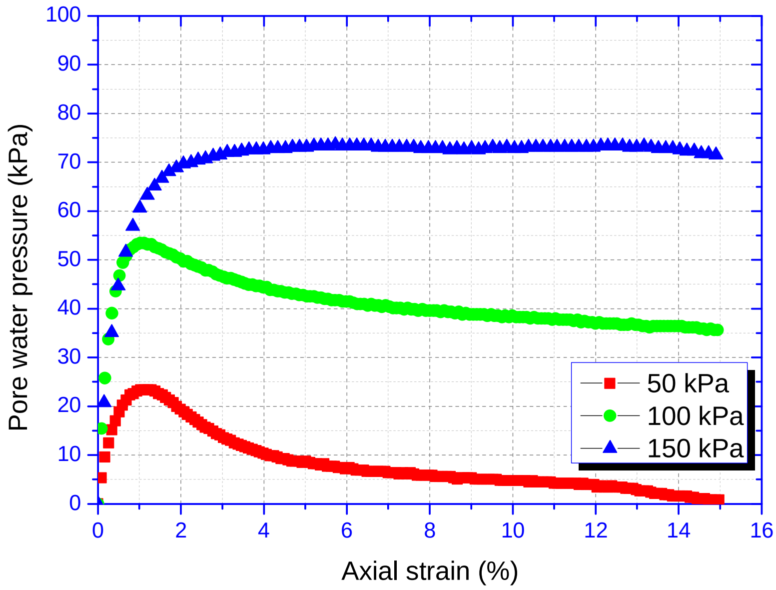


Fig. 4.10 Pore pressure results versus axial strain for small triaxial test

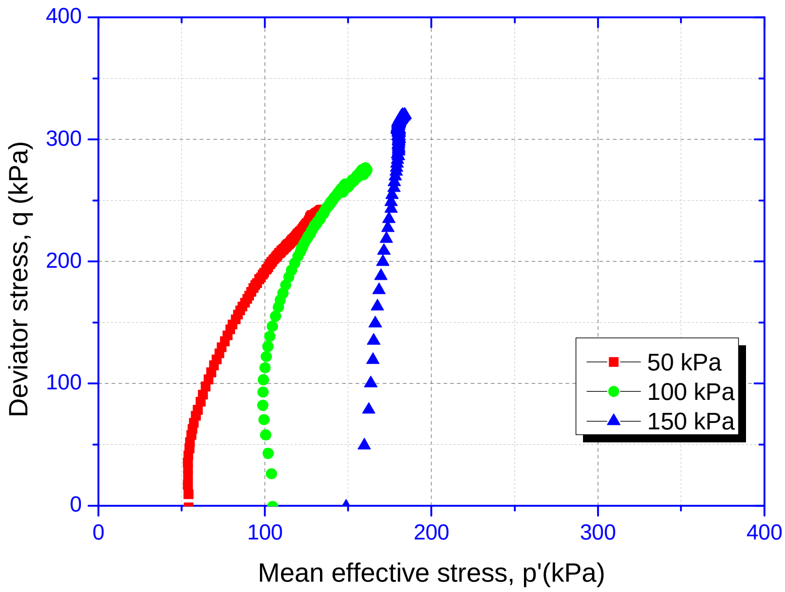


Fig. 4.11 Stress paths for small triaxial test

Figure 4.11 shows stress paths for samples in small triaxial test. From the beginning, stress paths showed an increase of pore pressure with the stress path moving to the left until pore pressure reduces and the effective pressure increases moving the stress path into the right direction.

4.4.3 Effect of particle size on shear strength of waste mixture sample

In order to compare the peak strength envelopes and the shear strength parameters for large and small samples, the shear strength parameters are determined using a linear interpolation. Figure 4.12 shows the peak strength of small samples and large samples. The shear strength parameters-cohesion intercept *c*' and the angle of friction ϕ'- associated with these peak strength envelopes can be obtained using the following two equations:

$$\phi' = sin^{-1}\left(\frac{3M}{6+M}\right) \tag{4.3}$$

$$c' = f\left[\frac{3-\sin(\phi')}{6\,cos(\phi')}\right] \tag{4.4}$$

where *M* is the slope of peak strength envelope and *f* is the q-intercept of the peak strength envelopes in p'-q stress space.

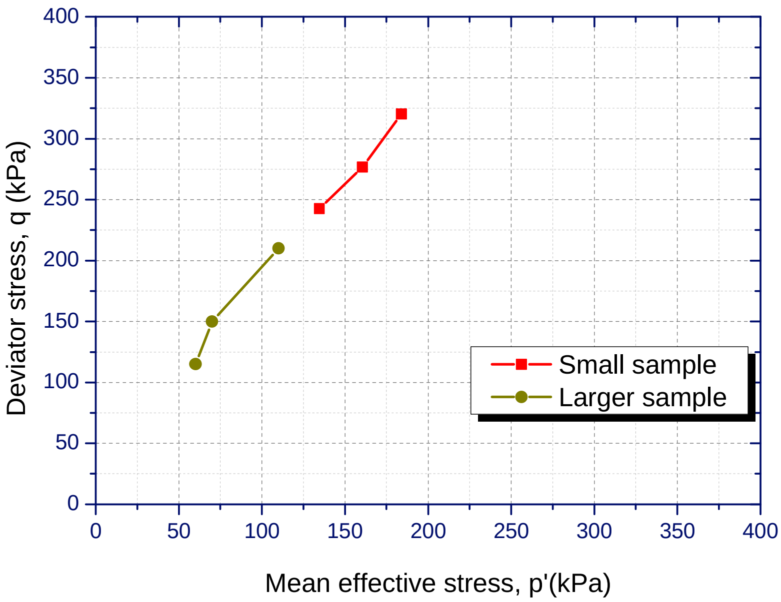
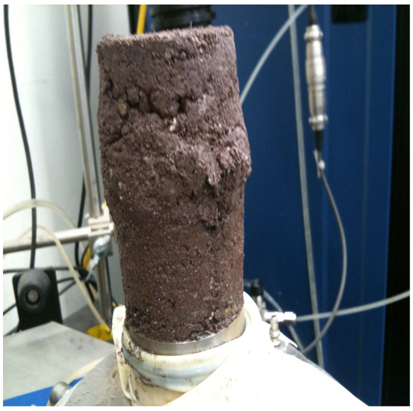


Fig. 4.12 Peak strength envelopes of small samples and large samples

Table 4.3 Shear strength parameters results

Tests	ϕ'(°)	c'(kPa)
Small triaxial test	46.7	0
Large triaxial test	44.78	2.8



Failure for initial sample with 5x10 cm

Failure for large sample with 15x30 cm

Fig. 4.13 Sample failure for small and large specimen

The shear strength parameters are shown in Table 4.3. The cohesion and angle of friction obtained are 0 kPa, 46.7° for small sample, and 2.8 kPa, 44.78° for large sample, respectively. The direction of peak strength envelope for samples and larger samples is similar. Thus, the strength parameters results are almost no change. The most important reason for the change in shear strength is related to pore water pressure generated. In the large sample, due to large diameter of mixture waste and large specimen the pore water pressure generated are higher compare to those in small samples. The change in pore water pressure contributed to the change in shear strength of large sample compare with small samples. Thus, most important reason for the change in shear strength is related to pore water pressure generated. In the large sample, due its the large diameter, the pore water pressure generated is higher compare to the results obtained for small samples. The change in pore water pressure contributed to the increased in shear strength for large sample compare with small samples.

The differences in stress paths for small and large samples could be related to the crushability of the larger samples. The crushability of larger samples were observed in Table 4.2, although the initial of dry density for small and large samples are the same but the void ratio were reduced in consolidated step for large samples compared with small samples. These results showed that the volume of large samples was reduced due to crushability. This behavior has been observed in a previous research conducted by Kokusho (2004) and described early in this chapter.

The two major factors governing the shear strength of granular materials are interlocking between particles and particle breakage. The interlocking between particles increases the shearing resistance, while the breakage of particles decreases the shear strength. In this test, the larger samples had larger breakage of particle and that lead to lower shear strength compare with results obtained from small samples. The results of this study show that as the size of particles increase, the shear strength of waste mixture decreases. These results are consistent with results presented by Kirkpatrick (1965); Fragaszy et al. (1990) and Kokusho et al. (2004).

4.5 Summary

Based on the experimental results, the following summarizes about the scale effects of specimens on the mechanical properties of waste mixture in coastal landfills:

1) In coastal landfill sites, the presence of large particles in waste mixture can change the results of triaxial test. It is necessary to estimate the change of shear strength if the waste mixture sample contains large particles. Thus, the comparison between small and large triaxial test is necessary to understand better the shear strength behavior and pore water generated from waste mixture samples. In this research, the particle size of the larger samples for large triaxial test 15cmx30cm is larger than 9.5mm. In the large triaxial test, the pore water pressure generated is higher compared to the results obtained for small samples due to the longer dissipation time of pore water pressure.

2) The shear strength for small samples is higher than those of large samples. However, the direction of peak strength envelope for samples and larger samples is similar. Thus, the strength parameters results are almost no change. It is suggested that the change in pore water pressure contributed to the changes in stress paths and shear strength of material. The differences in stress paths for small and large samples could be also related to the crushability of the samples.
3) The test results showed that an increase in diameter of particle size does not changed the shear strength parameters of waste mixture in coastal landfill site. However, if a rapid loading act on the waste mixture in coastal landfill sites, the change of pore water pressure generated for large samples should be consider to prevent the instability of slope. Moreover, the crushability of larger samples can increase the settlement of coastal landfill sites.

CHAPTER 5: EFFECTS OF THE BIODEGRADATION ON THE MECHANICAL PROPERTIES OF MUNICIPAL SOLID WASTE IN BIOREACTOR LANDFILLS

5.1 General Remarks

Landfilling is a primary disposal method for municipal solid waste (MSW) in many countries including Vietnam. The predominant forms of waste disposal facility in Vietnam are open and controlled dumping sites. Most of them do not have a necessary liner system or a cover system (Nguyen 2004), can not ensure landfill stability and pose various environmental problems such as potential ground water contamination and emission of uncontrolled landfill gases.

Recently, the use of bioreactor landfill has increased due to its many advantages: increase in rates of gas production; increase waste stabilization; increase in rate of landfill settlement; and decrease in leachate disposal and postclosure cost (Reinhart et al. 2002). Therefore, bioreactor landfills should be considered an appropriate alternative to address landfill management problems in Vietnam.

In bioreactor landfill, leachate is recirculated to enhance waste biodegradation and the geotechnical properties of waste are expected to change with time due to this process. Thus, we should consider the time dependency (aging) on the mechanical properties of waste in this type of reactors. In bioreactor landfills, waste biodegradation is related to the changes of the mechanical properties of the waste. Compressibility and shear strength are the most important parameters to be considered.

The compressibility characteristics of waste are of special concern when designing temporary and final closure covers for landfills (Hettiarachchi et al. 2009). The compressibility of MSW is commonly estimated using the theory of one-dimensional consolidation (Fassett et al. 1994; Hossain et al. 2003), with the total settlement divided into primary and secondary components (Sowers 1973). Previous researches have performed settlement experiments to investigate the effect of MSW degradation on the compressibility characteristics of waste in bioreactor landfills. It has been found that the rate of landfill settlement depends primarily on waste composition, operational practices and factors affecting biodegradation (Wall 1995; Hossain et al. 2003; Hettiarachchi et al. 2009).

There are few studies about the effect of biodegradation on the mechanical properties of municipal solid waste in a bioreactor landfill. In addition, regarding the impact of biodegradation on the strength of MSW, the results reported by researchers are not consistent. While some researchers pointed out that shear strength decreased with an increase in MSW decomposition (Hossain 2002; Hossain and Haque 2009), other researchers reported an increase in shear strength with decomposition of waste (Reddy et al. 2009a; Machado et al. 2010). Therefore, selection of appropriate shear strength parameters during the waste biodegradation process remains a challenging issue for bioreactor landfill design.

In this research, laboratory-scale bioreactor landfills were employed to investigate the degradation of waste using samples that reached the anaerobic decomposition phase. A series of consolidation tests and consolidated undrained triaxial tests were carried out on these MSW samples to evaluate the biodegradation effects on the compressibility and shear strength properties.

5.2 Materials and methods

5.2.1 Synthetic municipal solid waste preparation

The composition of MSW in Hanoi city (Vietnam) is nearly 51% biodegradable (organic materials, paper and textiles) and 49% non-biodegradable (plastic, rubber, leather, wood, metal, glass and inert matter) by weight (see Fig. 5.1). Figure 5-2 shows the composition of the synthetic municipal solid waste (SMSW) used in this study, which simulates the composition of municipal solid waste in Vietnam (see Fig. 5.1). SMSW was shredded into 10 mm pieces, and then deionized water was added to adjust water content to 54.6% (wet weight basis).

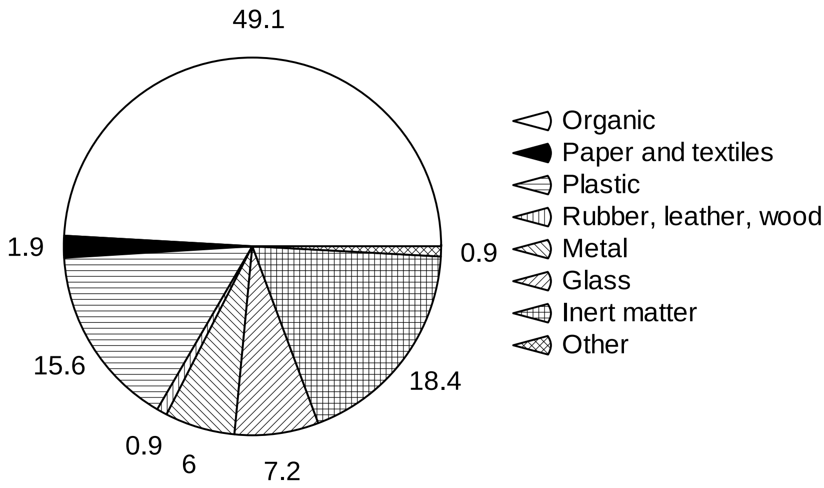


Fig. 5.1 Composition of MSW in Vietnam

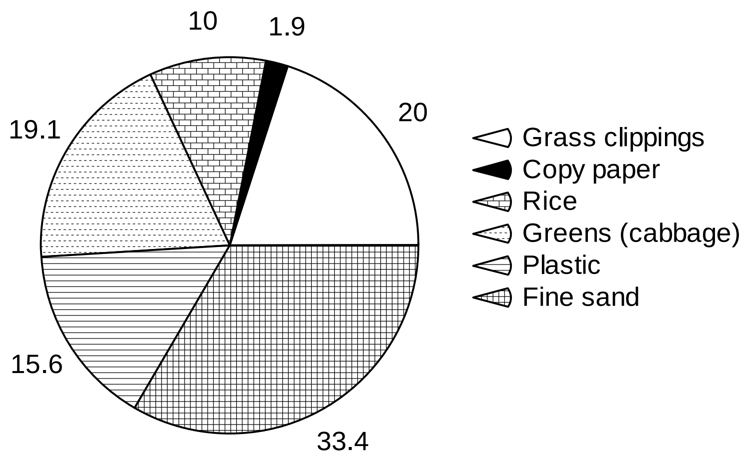


Fig. 5.2 Composition of SMSW

5.2.2 Bioreactor setup

The experimental setup of the lab-scale bioreactor landfills constructed to simulate a MSW landfill under anaerobic condition is shown in Fig. 5.3. Two bioreactor tests were run for a length of 35 and 118 days, respectively. In these tests, the internal temperature of the bioreactors was maintained at 35ºC ±0.1 ºC by using temperature controllers.

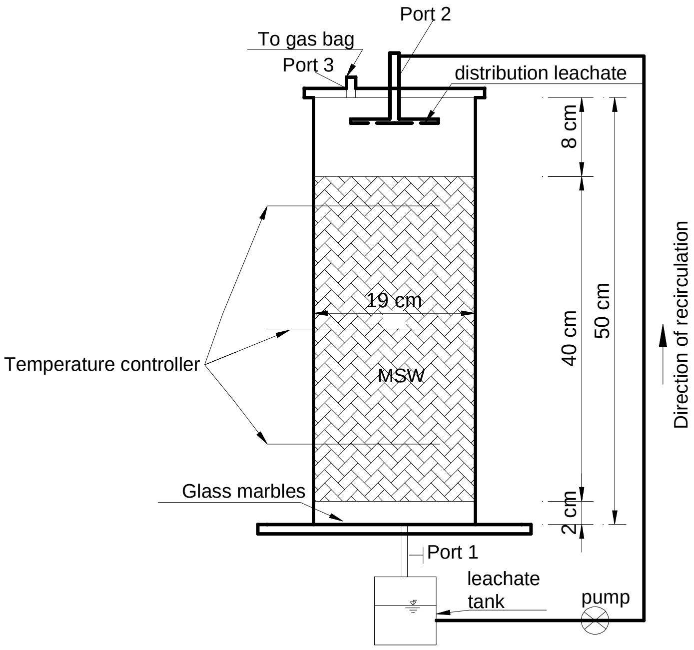


Fig. 5.3 The schematic of bioreactor experiment

The bioreactors were made of acrylic resin and had a 19 cm inner diameter and 50 cm height. These bioreactors were equipped with three ports: Port 1 was used for drainage; Port 2 was used to recirculate the leachate and Port 3 was used to collect gas generated by the decomposition. These bioreactors were filled with 8 kg of SMSW and the initial height of the SMSW layer was 40 cm. Leachate was stored in a 2 L plastic bottle at the bottom of bioreactor and recirculated with a 500 ml/d of flow rate using a peristaltic pump. Gas was collected in 5L and 10 L gas bags and the volume was measured by water displacement method. After sealing, the bioreactors were purged with nitrogen to displace oxygen from the system.

5.2.3 Degradation monitoring

During the time of the test, pH and chemical oxygen demand (COD) of the leachate as well as gas production were measured periodically for estimating the phase of waste. Figure 5.4 shows the pH for waste after 35 days, the pH of the leachate reached values below 5.7, therefore the waste material was considered to reach the anaerobic decomposition phase. After 118 days, the waste material was considered to reach the methane production phase, when the pH of the leachate was nearly 8 (See Fig 5.4). Then, SMSW was extracted and tested for physical characteristics, settlement and shear strength properties.

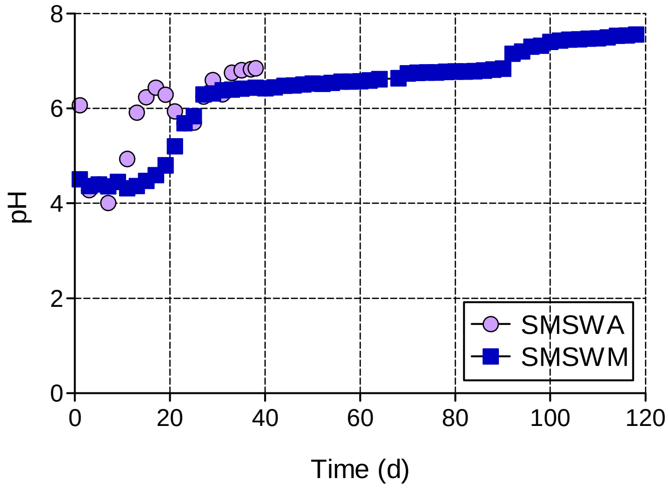


Fig. 5.4 pH for waste at anaerobic phase and methane phase

5.3 Mechanical properties of waste in bioreactor landfills

5.3.1 Physical tests

The SMSW after 35 days and 118 days accelerated decomposition are in an aerobic phase (SWSWA) and methane phase (SWSWM). These samples were subjected to various physical tests including particle size distribution test, wet water content, organic content and specific gravity according to Japanese Industrial Standard (JIS). These tests were also conducted for the initial SMSW before the decomposition (SMSWI).

5.3.2 Consolidation tests

A series of consolidation tests were conducted for SMSWI and SMSWA. Both waste samples were compacted into the consolidation ring (60 mm inside diameter and 20 mm in height). The water content of samples is shown in Table 5.1. Dry unit weight for SMSWI, SMSWA and SMSWM were 5.9; 6.3 and 6.6 kN/m^3, respectively. The loading method described by JIS A1217 was adopted to determine the coefficient of primary consolidation. Tests were run under a vertical stress range of 9.8-1256 kPa.

5.3.3 Consolidated undrained (CU) triaxial tests

The bioreactor landfill may become unstable if high pore water pressure is generated by leachate recirculation. Therefore, effective strength parameters should be carefully evaluated. In this research, consolidated undrained (CU) triaxial compression tests were conducted for SMSWI and SMSWA. Specimens were compacted at initial wet unit weight about 12 kN/m^3 by using a cylindrical split mold with 50 mm diameter and 100 mm height. Samples were saturated by applied vacuum procedure and back pressure of 240 kPa to get pore pressure coefficient (B) higher than 0.95. Samples were consolidated with effective confining pressures of 50, 100 and 150 kPa and sheared at a constant strain rate of 0.5%/min until 20% of strain.

5.4 Results and discussions

5.4.1 Physical tests

Table 5.1 summarized the physical properties and the particle size distributions for the SMSWI, SMSWA and the SMSWM samples. It can be seen that particle size of waste is reduced due to the biodegradation process in the bioreactor landfill.

Table 5.1 Physical properties of SWSWI, SMSWA, and SMSWM

Parameters	Water content (%)	Specific gravity (-)	Organic content (%)
SMSWI	54.7	1.57	47.5
SMSWA	56	1.80	36.9
SMSWM	60	1.83	30.8

Another important finding is that the specific gravity of the waste samples increases with the decomposition of the waste particles in the bioreactor landfill. This process is related to the reduction of organic content from 47.5% for fresh waste (SMSWI) to 36.9 % for waste in the anaerobic phase (SMSWA) and 30.8% for waste in the methane phase (SMSWM).

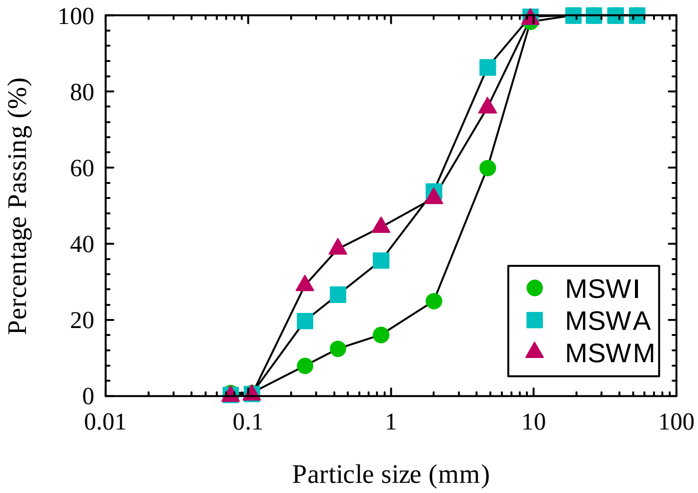


Fig. 5.5 Particle size distribution of waste at different phase

5.4.2 Consolidation characteristics

Figure 5.6 shows the change of axial strain versus consolidation pressure in log scale. The final cumulative strain under a pressure of 1256 kPa was approximately 46% and 30% for SMSWI and SMSWA, respectively. Compression ratio $C_{c\varepsilon}$ was used to calculate MSW settlement. $C_{c\varepsilon}$ is the slope of compression curves in Fig. 5.6 and it is related to the coefficient of primary consolidation C_c as shown in Eq. 5.1:

$$C_{c\varepsilon} = C_c/(1 + e_0) \quad (5.1)$$

where e_0 is initial void ratio of waste samples.

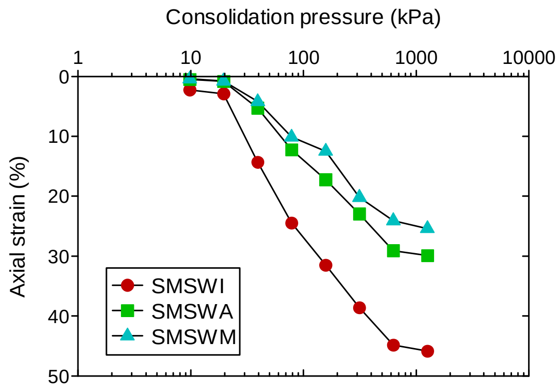


Fig. 5.6 Compressibility at different phases

The compression ratio of waste is shown in Table 5.2. SMSWI and SMSWM samples showed a higher compression ratio due to their bigger particle size and low dry density compare to that of SMSWA samples. This table also shows that the compressibility of the waste is governed by an increase in voids ratio due to solids loss.

Table 5.3 compares the results from this study with the compressibility of waste reported in previous research. The modified compression ratio varied from 0.16 to 0.35 (Landva 1990; Hossain 2002; Vilar and Carvalho 2004; Hettiarachchi et al. 2009; Reddy et al. 2009a; Reddy et al. 2009b). The modified compression ratios obtained from the consolidation test run in this research are within the range of values reported in the published literature.

Table 5.2 Compression ratio results

Type of waste	SMSWI	SMSWA	SMSWM
Initial void ratio	2.07	2.25	2.3
Compression ratio	0.24	0.16	0.14

Table 5.3 Compressibility of waste

Source	Age of MSW (years)	Test type	Modified compression ratio (C'_c)
This study	Fresh waste (SMSWI)	Laboratory	0.19
	Waste in anaerobic phase (SMSWA)	Laboratory	0.16
	Waste in methane phase (SMSWM)	Laboratory	0.14
Reddy *et al* (2009a)	Fresh	Laboratory	0.16 - 0.31
Reddy *et al*. (2009b)	1.5	Laboratory	0.19 - 0.24
Reddy *et al*. (2009c)	Fresh	Laboratory	0.24 – 0.33
Hettiarachchi (2005)	Fresh	Laboratory	0.18 – 0.21
Hossain *et al*. (2002)	Fresh	Laboratory	0.16 – 0.25
Landva & Clark (1990)	Fresh	Laboratory	0.35
Dermusoglu *et al*. (2006)	10	Laboratory	0.13 – 0.26
Vilar & Carvalho (2004)	15	Laboratory	0.21

In order to estimate the long-term settlement of waste samples, consolidation tests were conducted under constant stress of 88.3 kPa during 25 days. Figure 5.7 shows the relationship between axial strain and elapsed time for SMSWI and SMSWA samples under a constant pressure of 88.3 kPa. The rate of long-term settlement was quantified using the modified secondary compression index $C'_{\alpha\varepsilon}$ as shown in Eq. 5.2:

$$C'_{\alpha\varepsilon} = \Delta\varepsilon / log\Delta t \tag{5.2}$$

where $\Delta\varepsilon$ is a change of axial strain and log Δt is the change of time (see Fig. 5.9).

Using Eq. 5.2, the modified secondary compression index ($C'_{\alpha\varepsilon}$) of SMSWI and SMSWA were 0.01 and 0.006, respectively. These results show similar behavior with primary consolidation of waste.

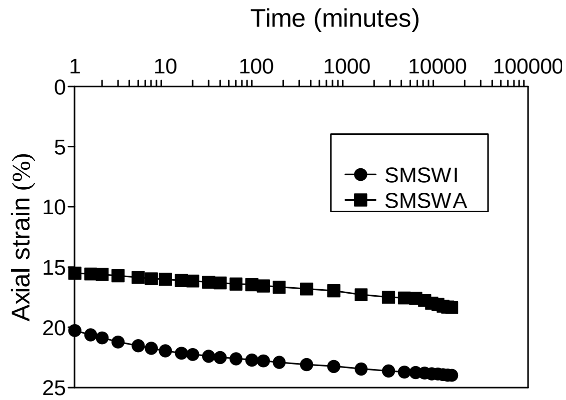


Fig. 5.7 Axial strain versus log time for long-term settlement

The modified secondary compression index (C'_{α}) of fresh waste and waste in anaerobic phase were calculated and summarized in Table 5.4. The results show that secondary compression ratio is not constant. The lower density of fresh waste may cause the larger value of C'_{α} than that of waste at anaerobic phase.

Table 5.4 Secondary compression ratio

Source	Modified Secondary Compression ratio
This study	0.01 (Fresh waste) 0.006 (Waste in anaerobic phase)
Hossain et al (2002)	0.05–0.22
Wall and Zeiss(1995)	0.033-0.056
Gabr and Valero(1995)	0.015-0.023
Boutwell and Fiore (1995)	0.006-0.012
Fassett et al. (1994)	<0.1
Landva & Clark (1990)	0.35
Bjarngard and Edgers (1990)	0.004-0.04
Oweis & Khera (1990)	0.001–0.04
Landva et al. (1984)	0.0005-0.029

5.4.3 CU shear strength properties

Typical stress- strain curves for SMSWI, SMSWA and SMSWM were introduced in Fig. 5.8 to Fig. 5.10. Deviator stress increases with axial strain almost continuously, without any peak in the stress-strain curve which is consistent with results obtained by other researcher (Grisolia and Napoleoni 1996; Machado et al. 2006). This mechanical respond could be related to the reinforcement of fiber material (15.6% of plastic material with respect to the total weight) in the composition of SMSW.

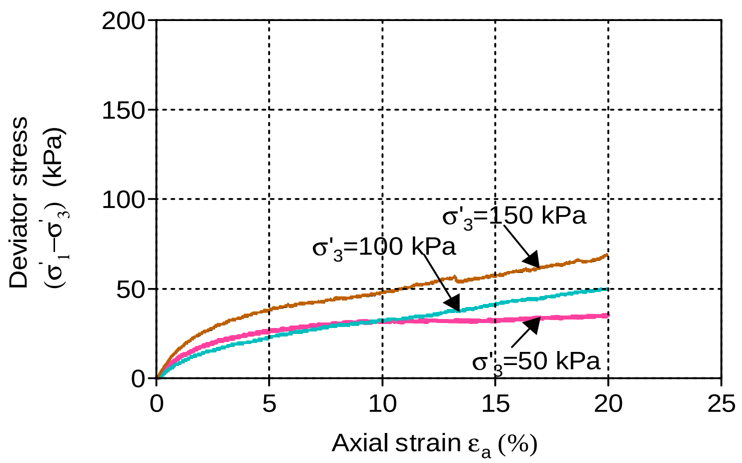


Fig. 5.8 Stress-strain behavior for SMSWI

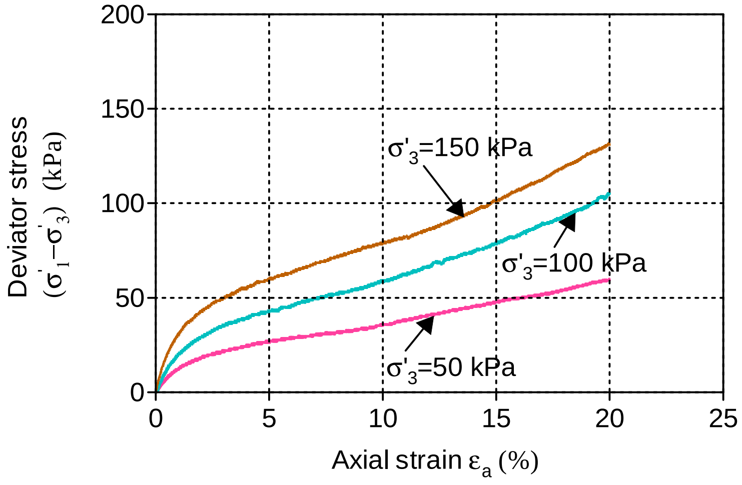


Fig. 5.9 Stress-strain behavior for SMSWA

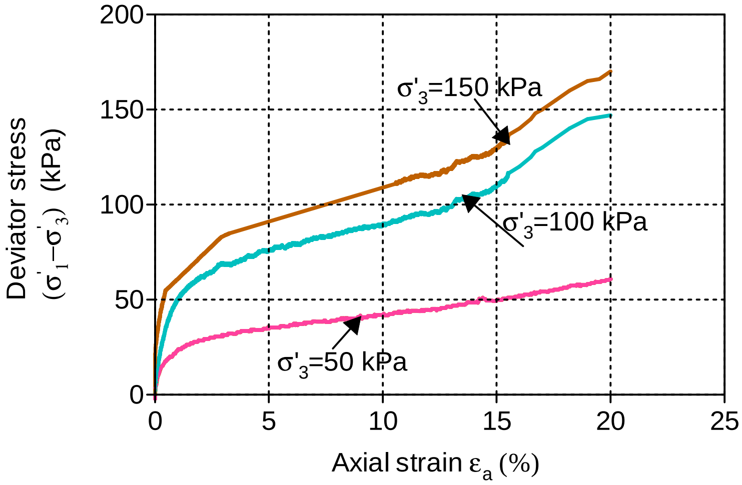


Fig. 5.10 Stress-strain behavior for SMSWM

The relation between pore water pressure versus axial strain for SMSWI, SMSWA, and SMSWM are presented in Fig. 5.11 to 5.13, respectively. From these figure it can be observed that pore water pressure under initial conditions is higher that during the anaerobic phase and the methane phase.

The results were interpreted in terms of the deviator stress (q) and the effective mean pressure (p'), following Eq.5.3 and Eq.5.4, where σ'_1 and σ'_3 are the effective axial and confining stresses.

$$q = (\sigma'_1 - \sigma'_3) \tag{5.3}$$

$$p' = (\sigma'_1 + 2\sigma'_3) \tag{5.4}$$

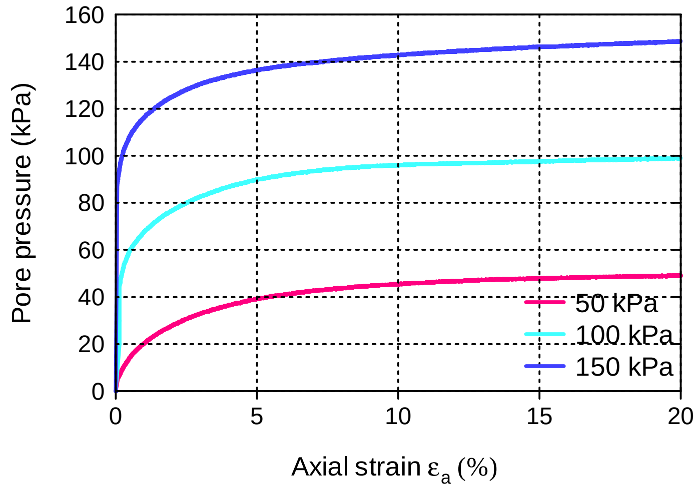


Fig. 5.11 Pore water pressure for SMSWI

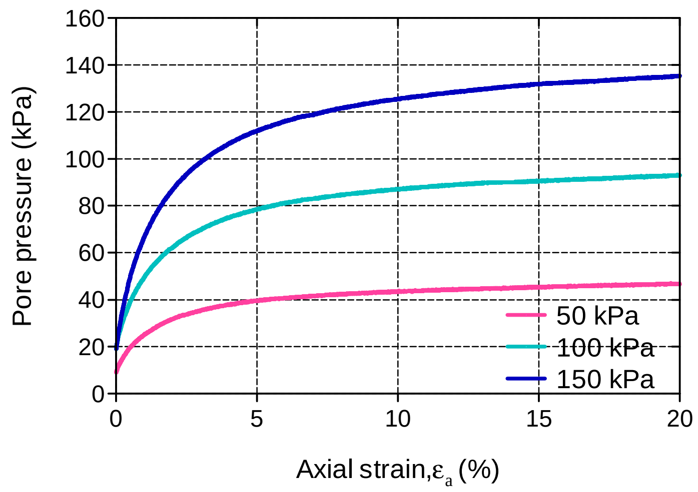


Fig. 5.12 Pore water pressure for SMSWA

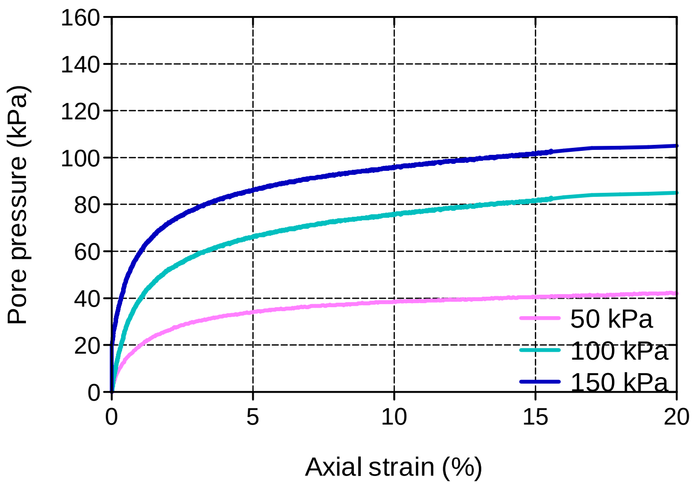


Fig. 5.13 Pore water pressure for SMSWM

Due to the lack of peak strength, shear strength obtained at 15% of axial strain is used to plot the strength envelope in p', q plane (see Fig.5.14). As the slope strength envelope of the SMSWM and SMSWA samples increases, higher shear strength is observed in these samples than in the SMSWI samples.

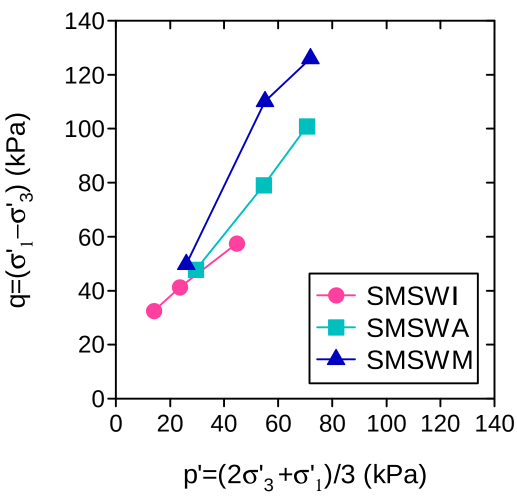


Fig. 5.14 Strength envelope for SMSWI, SMSWA and SMSWM

Shear strength parameters results are presented in Table 5.5. These results show an increase of friction angle but a decrease in cohesion of MSW. The increase of friction angle of SMSWA and SMSWA could be explained by the change of waste structure. Decreases in particle size and organic content are the result of the biodegradation process. Therefore, the increase in the density of the waste layers and the changes in the porous structure caused an increase in the friction angle during the anaerobic phase. Figure 5.15

compares the CU results of this research with previous studies. The results show that the higher organic content of waste samples leads to higher cohesion results. The trend of MSW behavior in this study characterized by a trend where a decrease in cohesion and an increase in the angle of friction with MSW age are observed. This trend is similar to the observed in the results presented by Reddy et al. (2009a).

Table 5.5 Strength parameters results

Phase	ϕ'	c'
SMSWI	20.8	10.1
SMSWA	32.0	4.6
SMSWM	41.2	4.4

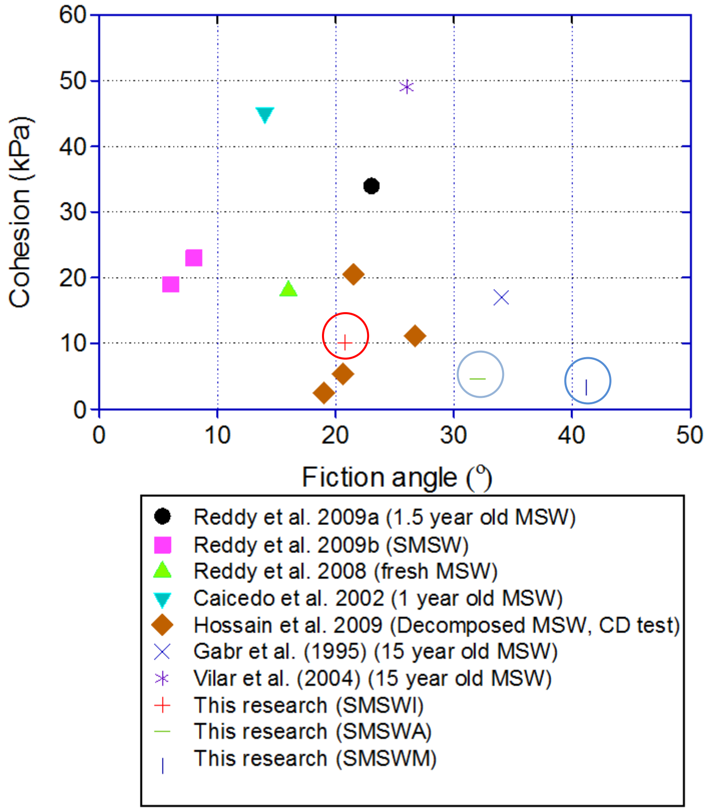


Fig. 5.15 Shear strength parameters

5.5 Summary

Based on the experimental results, the MSW behavior observed during the consolidation and triaxial tests can be summarized as follows:

1) In bioreactor landfills, waste mass is reduced due to biodegradation of organic content such as food waste and garden waste and paper products. The organic material is converted to CO_2 and methane. In this research, the results of lab-scale bioreactor tests showed that particle size and pore structure of MSW are reduced due to biodegradation of waste. The consolidation tests showed that the compression indexes are reduced due to biodegradation process. These results are consistent with previous research. In the consolidation tests, MSW samples were prepared under disturbed and normally consolidated conditions. Thus, the consolidation test does not consider the biodegradation progress during consolidation test that might affect the results of compression index when conducting long-term settlement. The combination of settlement and biodegradation in one facility would be suitable to estimate the settlement of MSW in bioreactor landfills. In real bioreactor landfill sites, the volume of waste decreases due to biodegradation and the dry density might decrease for fresh waste. However, the density is increased for the degraded waste, if the waste layers are compacted. Thus, the results of this research should be carefully used to estimate the settlement of MSW in bioreactor landfill.
2) It is necessary to understand the change of settlement of MSW landfills over time. The long-term settlement was estimated by consolidation tests. The modified secondary compression index ($C'_{\alpha\varepsilon}$) was not constant for waste samples as it was observed for soil samples. From test results, it was observed that $C'_{\alpha\varepsilon}$ decreases as the waste degradation increases. Thus, using a single value of $C'_{\alpha\varepsilon}$ may lead to unrealistic settlement estimates of landfills. It is suggested that the changes of secondary compression index should be considered for calculating the settlement and stability of bioreactor landfills.
3) In this research, the stabilization phase of MSW in bioreactor landfills has not been defined due to the lack of gas composition for leachate. Thus, the consolidation and triaxial test results do not take into consideration the stabilization phase of MSW in bioreactor landfills.

4) CU test results showed that the stress-strain has a concave curves and peak deviator stress are not reached until 20% of axial strain. The strength parameters showed the increase in the friction during the anaerobic condition due to the a) increase in the density of the waste layers, b) the changes in the porous structure of MSW samples, and c) the reinforce component in MSW composition (plastic is 16%).
5) The cohesion of MSW samples decreased with MSW biodegradation due to the reduction of organic content. It is strongly recommended to consider the changed of cohesion for stability of bioreactor landfills.

CHAPTER 6: PRACTICAL IMPLICATIONS

6.1 Coastal landfill sites

The shear strength parameters are important for estimating the stability of coastal landfills. In this research, the aging effect on the shear strength of the waste mixture layer in coastal landfill sites was studied in Chapter 3 and the results showed that the shear strength of samples increased with curing time. The shear strength of the waste mixture samples ranged from about 250 kPa to 650 kPa.

The results also showed that the increased in shear strength is not related to the bonding effect or the friction angle of the waste mixture sample. However, the change of density is an important factor on the development of shear strength. Therefore, the density of the waste mixture layers should be carefully investigated in coastal landfill sites.

Another factor that is important to determine in order to utilize a coastal landfill site after closure is the bearing capacity of the waste mixture layer. The bearing capacity determines the capacity of the waste mixture layer to support foundations and therefore defines its geotechnical performance. The results of this research showed that waste mixture samples exhibited a self-hardening behavior with a shear strength capacity > 200 kPa. This bearing strength capacity can be used for basic structures, such as houses, according to the Japan Waste Management Consultant Association where an N-value=15-30 or allowance bearing capacity of 100-200 kPa is required (JWMCA 1994).

In the case of waste mixture has the particle size large than 9.5mm, results of this research suggested that it is necessary to used the large triaxial test for investigating the shear strength behavior. Although an increase in diameter of particle size does not change the shear strength parameters of waste mixture in coastal landfill site. However, the pore water pressure generated for large samples in larger triaxial test are much higher than those of small samples. Thus, if a rapid loading act on the waste mixture in coastal landfill sites, the change of pore water pressure generated for large samples should be consider to prevent the instability of slope. Moreover, the crushability of larger samples can increase the settlement of coastal landfill sites.

6.2 Bioreactor landfills

Bioreactor landfills are operated to enhance refuse decomposition and waste stabilization by implementing leachate recirculation. In general, waste biodegradation leads to changes in the physical and mechanical properties of waste. This study tested synthetic MSW (SMSW) with controlled composition to observe the changes of the mechanical properties of MSW with the degradation process. In the case of settlement, the compression index and modified secondary compression index are not constant. These parameters change with the degradation process. Therefore, to calculate the settlement of the waste layer in a bioreactor landfill; it is suggested that the waste layer should be divided into the separate layers depending on their degradation phase. This approach may improve the accuracy of the estimation of the waste settlement in bioreactor landfills.

The waste in a bioreactor landfill does not have a single age, but rather have different ages associated with their respective stabilization stages (Hossain 2009). The age of the waste in a MSW landfill can be divided into different degradation phases such as aerobic, anaerobic, methane, etc. As time passes by, the solid waste layers are expected to move to next phase of decomposition. Finally after complete stabilization, all solid waste layers would be at the final stage of decomposition. In the same way, shear strength parameters for solid waste will change, causing concern for landfill slope stability.

In this research, the shear strength parameters (cohesion and friction angle) were measured during the CU tests. From the results, cohesion ranged from 4.4 to 10.1 kPa and friction angle varied from 20.8° to 41.2°. The cohesion was reduced with the degradation and this increased the concerns for the stability of bioreactor landfills. The changes in the geotechnical properties of the MSW due to waste degradation should be accounted in the analysis and design of landfills, particularly bioreactor landfills.

Leachate recirculation places concerns for the landfill stability under undrained condition. The effective shear strength parameters obtained in this research are very important to estimate the stability of a bioreactor landfill. Using the changes of shear strength with degradation, MSW within a landfill can be divided into different layers with changes of strength properties. These data can then be input into a modelling program to predict stability.

Due to the heterogeneous nature of landfills, computer modelling of the waste layer requires analysis with experimental data from bioreactor landfills is needed and all of the tests results in this study might be utilized to assess the stability and settlement of bioreactor landfill. For slope stability analysis of bioreactor landfills, it is needed to consider site-specific conditions in order to make reasonable estimation for slope stability.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The main results of this research are summarized as follows:

In chapter 3, the author discussed the mechanical properties of the waste layer in a coastal landfill site. In this chapter, mechanical tests such as CU triaxial test and hydraulic conductivity were carried out in the initial and cured samples in simulated leachate for 180 days. The CU test results showed that the shear strength of waste mixture samples increased with curing time and the pore pressure had a significant impact on shear strength development. However, cohesion and friction angle do not change with curing period. Therefore, an important finding is that the increase in shear strength with curing time is not due to cementation or bonding effects but only to densifications of waste mixture samples due to hydration. The mechanism of this behavior is the waste mixture crystals and the hydration products are considered to have the same cohesion and friction angle and that lead to no changes in cohesion or friction angles in the specimen cured in simulated leachate in coastal landfills. The SEM and XRD also confirmed the mechanism of curing waste mixture in coastal landfill sites. The results from the SEM and XRD analysis showed an increase in the formation of ettringite and other hydration products, such as CSH, with curing time, the increase of shear strength due to densification of sample. In addition, the trend of pore water pressure generated was that initial peak pore water pressure increased as curing time increased and final pore water pressure decreased. The larger curing period, the higher density and an increase in dilatancy of waste mixture samples are. It was also found that the effect of dilatant behavior is higher in samples under small confining pressure than in samples under high confining pressure. The pore water pressure contributed to the increase in stress paths and strength of waste mixture samples as increased curing time. Moreover, waste mixture samples showed an increase in the modulus of elasticity with curing time. This trend is consistent with the increase of shear strength of waste mixture samples.

In chapter 4, large-scale triaxial test and a small triaxial test were conducted in waste samples. This chapter deals with the effects of large particle size on the shear strength of waste mixture samples. In the case of waste mixture has the particle size large than 9.5mm, results of this research suggested that it is necessary to used the large triaxial test to investigate the shear strength and pore water pressure generated behavior in large sample. The large specimen had 15 cm in diameter and 30 cm in height, while small specimen had 5 cm in diameter and 10 cm in height. The CU triaxial test results showed that the peak deviator stress of large specimens was smaller than the one observed in small specimens. Although an increase in diameter of particle size does not change the shear strength parameters of waste mixture in coastal landfill site. However, the pore water pressure generated for large samples in larger triaxial test are much higher than those of small samples due to longer time dissipation of pore water pressure in large samples. Moreover, the crushability of large samples is another factor that contributes to the change of pore water pressure and peak deviator stress in large samples.

In chapter 5, lab-scale bioreactor tests were conducted to simulate MSW bioreactor landfill under anaerobic condition. Synthetic MSW (SMSW) was used in the tests. Then, SMSW was extracted and tested for physical characteristics, settlement and shear strength properties. The results of lab-scale bioreactor tests showed that particle size and pore structure of MSW are reduced due to biodegradation of waste. The consolidation tests showed that the compression indexes are reduced due to biodegradation process. These results are consistent with previous research. However, in the consolidation tests, MSW samples were prepared under disturbed and normally consolidated conditions. Thus, the consolidation test does not consider the biodegradation progress during consolidation test that might affect the results of compression index when conducting long-term settlement. In the case of CU test, the results showed that the stress-strain has a concave curves and peak deviator stress are not reached until 20% of axial strain. The strength parameters showed the increase in the friction during the anaerobic condition due to the a) increase in the density of the waste layers, b) the changes in the porous structure of MSW samples, and c) the reinforce component in MSW composition (plastic is 16%). In addtion, the cohesion of MSW samples decreased with MSW biodegradation due to the reduction of organic content.

7.2 Recommendations and future research

7.2.1 Coastal landfill sites

In coastal landfill sites, the long-term deformation properties of the waste mixture layer are an important issue. In this study, it was observed that the hydraulic conductivity of waste mixture samples decreased with curing time and that in turn change the rate of consolidation of the waste mixture layer in coastal landfill sites. Therefore, studying the long term deformation of the waste mixture layer should be considered for analysis in future research.

As shown chapter 3, the effects of pore pressure behavior due to changes in the structure of the voids lead to an increase in the shear strength of the waste. Therefore, it is necessary to consider the shear strength of the specimen structure by Consolidated drained (CD) triaxial compression tests. In addition, the seismic loading should be taken into account in triaxial tests to estimate the stability of coastal landfill sites.

7.2.2 Bioreactor landfills

In this research, the consolidation tests were carried out on disturbed MSW samples that may affect results. In the future, undisturbed samples should be considered. In addition, a combination of settlement and biodegradation in one facility would be suitable to estimate the settlement of MSW in bioreactor landfills. In real bioreactor landfill sites, the volume of waste decreases due to biodegradation and the dry density might decrease for fresh waste. However, the density is increased for the degraded waste, if the waste layers are compacted. Thus, the results of this research should be carefully used to estimate the settlement of MSW in bioreactor landfill.

It is recommended to take into account the biodegradation process when determining the mechanical properties of MSW for design and construction of bioreactor landfills. It may be very important issue for engineering designers to evaluate the stability of landfills by using a suitable shear strength value of MSW at different biodegradation levels.

Consolidated drained triaxial tests of MSW should be conducted for bioreactor landfills taking into account biodegradation to reach a better understanding of the behavior of MSW. This will help engineers to make good decisions in the design, construction as well as in the maintenance of bioreactor landfills. To estimate settlement and stability of bioreactor landfills, numerical analysis might suitable because it can be simulate bioreactor landfills model and then pore water pressure, consolidation and safety factor are calculated with the changes of biodegradation for MSW layers in the model.

Based on the information generated in this research, evaluation of failed waste slopes may provide useful insight.

REFERENCES

Aburatani, S., Hayashi, Y., and Nishikawa, T. (1996). "Offshore waste disposal by Osaka Bay Phoenix Project." In: *Environmental Geotechnics*, M. Kamon, ed., Balkema, Rotterdam, Netherlands, 623-628.

ADB. (2011). "Toward sustainable municipal organic waste management in South Asia: A guidebook for policy makers and practitioners." *Mandaluyong City, Philippines: Asian Development Bank.*

Alyousfi, A. B., Pohland, F. G., and Vasuki, N. C. (1993). "Design of landfill leachate recirculation systems based on flow characteristics." *Proceedings of the 47th Industrial Waste Conference*, 491-500.

Ariizumi, M. (1977). "Mechanism of lime stabilized soil." *Soil and Foundations*, 227, 9-15.

Barlaz, M. A., and Reinhart, D. (2004). "Bioreactor landfills: progress continues." *Waste Management*, 24(9), 859-860.

Barlaz, M. A., Schaefer, D. M., and Ham, R. K. (1989). "Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill." *Apply Environ. Microbiol.*, 55(1), 55–65.

Baxter, C. D. P., and Mitchell, J. K. (2004). "Experimental study on the aging of sands." *Journal of Geotechnical and Geoenvironmental Engineering*, 130(10), 1051-1062.

Becquart, F., Bernard, F., Abriak, N. E., and Zentar, R. (2009). "Monotonic aspects of the mechanical behaviour of bottom ash from municipal solid waste incineration and its potential use for road construction." *Waste Management*, 29(4), 1320-1329.

Cerato, A. B., and Lutenegger, A. J. (2006). "Specimen size and scale effects of direct shear box tests of sands." *Geotechnical Testing Journal*, 29(6), 507-516.

Chen, L., and Lin, D.-F. (2009). "Stabilization treatment of soft subgrade soil by sewage sludge ash and cement." *J. Hazard. Mater.*, 162(1), 321-327.

Consoli, N. C., Heineck, K. S., Coop, M. R., Fonseca, A. V. D., and Ferreira, C. (2007). "Coal bottom ash as a geomaterial: Influence of particle morphology on the behavior of granular materials." *Soil and Foundations*, 47(2), 361-373.

Das, S. K., and Yudhbir. (2006). "Geotechnical properties of low calcium and high calcium fly ash." *Geotechnical and Geological Engineering*, 24, 249-263.

Doi, Y., Shigeyoshi, I., and Yamada, M. (2000). "Change of the mechanical properties of MSW-incinerated ash with the lapse of time." In: *Proceedings of JSCE*, 103–112.

Edil, T. B., and Berthouex, P. M. (1990). "Earthen barriers technology for waste containment." *Waste Management*, 10(2), 147-153.

Eid, H. T., Stark, T. D., Evans, W. D., and Sherry, P. E. (2000). "Municipal solid waste slope failure I: waste and foundation soil properties." *Journal of Geotechnical and Geoenvironmental Engineering*, 126(5), 397-407.

Elagroudy, S. A., Abdel-Razik, M. H., Warith, M. A., and Ghobrial, F. H. (2008). "Waste settlement in bioreactor landfill models." *Waste Management*, 28(11), 2366-2374.

Fassett, J. B., Leonards, G. A., and Repetto, P. C. (1994). "Geotechnical properties of municipal solid waste and their use in landfill design." *Proceedings of the Waste Tech '94 Solid Waste Association of North America*, 1–31.

Fragaszy, R., Su, W., and Siddiqi, F. (1990). "Effects of oversize particles on the density of clean granular soils." *Geotechnical Testing Journal,* 13(2), 106-114.

Fragaszy, R. J., Su, J., Siddiqi, F. H., and Ho, C. L. (1992). "Modeling strength of sandy gravel." *Journal of Geotechnical Engineering-ASCE*, 118(6), 920-935.

Gabr, M. A., and Valero, S. N. (1995). "Geotechnical properties of municipal solid waste." *Geotechnical Testing Journal*, 18(2), 241-251.

Gotoh, K., Yahanaka, M., and Ogawa, T. (1998). "An experimental study on static and dynamic mechanical properties of municipal bottom ash." *Research Report, Faculty of Engineering, Nagasaki University* 28(51), 173-178.

Hennes, R. G. (1952). "The strength of gravel in direct shear." *ASTM special technical publication*, STP 131, 51-62.

Hettiarachchi, H., Meegoda, J., and Hettiaratchi, P. (2009). "Effects of gas and moisture on modeling of bioreactor landfill settlement." *Waste Management*, 29(3), 1018-1025.

Holtz, W. G., and J., G. H. (1956). "Triaxial shear tests on pervious gravelly soils." *Journal of the Soil Mechanics and Foundation Division*, 82, 1-22.

Hossain, M. D. S., and Haque, M. A. (2009). "The effects of daily cover soils on shear strength of municipal solid waste in bioreactor landfills." *Waste Management*, 29(5), 1568-1576.

Hossain, M. S. (2002). "Mechanics of compressibility and strength of solid waste in bioreactor landfills," PhD thesis, North Carolina State, Raleigh, NC.

Hossain, M. S., Gabr, M. A., and Barlaz, M. A. (2003). "Relationship of compressibility parameters to municipal solid waste decomposition." *Journal of Geotechnical and Geoenvironmental Engineering*, 129(12), 1151–1158.

Hossain, M. S., Gabr, M.A., & Barlaz, M.A. (2003). "Relationship of compressibility parameters to mu-nicipal solid waste decomposition." *Journal of Geotechnical and Geoenvironmental Engineering*, 129(12), 1151–1158.

Inazumi, S. (2011). "Hydraulic conductivity of steel pipe sheet pile cutoff walls at coastal waste landfill sites." *Integrated Waste Management - Volume I, Mr. Sunil Kumar (Ed.).*

Inazumi, S., Kimura, M., and Kamon, K. (2008). "Environmental designs for cutoff walls in coastal landfill sites." *Journal of the Southeast Asian Geotechnical Society*, 39(1), 19-24.

Itoh, T., Towhata, I., Kawano, Y., Kameda, M., Fukui, S., Koelsch, F., and Yonai, Y. (2005). "Mechanical properties of municipal waste deposits and ground improvement." In: *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, 2273-2276.

JWMCA. (1994). "Research report landfill stabilization." *Japan Waste Management Consultant Association*.

Kamon, K., and Katsumi, T. (2001). "Clay liners for waste landfill." *Clay Science for Engineering, K.Adachi and M.Fukue, eds., Balkema, Rotterdam*, 29-45.

Kamon, M., Gu, H., and I, M. (2001). "Improvement of mechanical properties of ferrum lime stabilized soil with the addition of aluminum sludge." *Materials Science Research International*, 7(1), 47-53.

Kamon, M., and Nontananandh, S. (1990). "Contribution of stainless-steel slag to the development of strength for seabed hedoro." *Soil and Foundations*, 30(4), 60-72.

Katsumi, T., Inui, T., and Kamon, M. (2009). " Geotechnical challenges at waste landfill sites in Japan." *International Symposium on Urban Geotechnics, Incheon, Korea*, 172-185.

Kirkpatrick, W. M. (1965). "Effect of grain size and grading on the shearing behavior of granular materials." In: *Proceedings of the sixth International Conference on Soil Mechanics and Foundation Engineering*.

Kjeldsen, P., Barlaz, M. A., Rooker, A. P., Baun, A., Ledin, A., and Christensen, T. H. (2002). "Present and long-term composition of MSW landfill leachate: A review." *Critical Reviews in Environmental Science and Technology*, 32(4), 297-336.

Kokusho, T., Hara, T., and Hiraoka, R. (2004). "Undrained shear strength of granular soils with different particle gradations." *Journal of Geotechnical and Geoenvironmental Engineering*, 130(6), 621-629.

Kondner, R. L. (1963). "Hyperbolic stress-strain response: cohesive soils." *Journal of Soil Mechanics and Foundation Engineering Division, ASCE*, 189(1), 115-143.

Lam, C. H. K., Ip, A. W. M., Barford, J. P., and McKay, G. (2010). "Use of incineration MSW ash: a review." *Sustainability*, 2(7), 1943-1968.

Landva, A. O., and Clark, J. I., ed. (1990). *Geotechnics of waste fill.*, Landva, A. O., and Clark, J. I. Ed., ASTM STP 1070, Philadelphia.

Landva, A. O., and Clark, J. I. (1991). "Geotechnics of waste fill : Proc Symposium on Geotechnics of Waste Fills - Theory and Practice, Pittsburg, 10-13 Sept 1989 P86-103. Publ Philadelphia: ASTM, 1990 (ASTM Special Technical Publication

1070)." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 28(6), A341-A341.

Machado, S. L., Karimpour-Fard, M., Shariatmadari, N., Carvalho, M. F., and Nascimento, J. C. F. d. (2010). "Evaluation of the geotechnical properties of MSW in two Brazilian landfills." *Waste Management*, 30(12), 2579-2591.

Machado, S. L., Vilar, O. M., and Carvalho, M. F. (2008). "Constitutive model for long term municipal solid waste mechanical behavior." *Computers and Geotechnics*, 35(5), 775-790.

Maeno, Y., Hirata, T., and Nagase, H. (1997). "Mechanical properties of bottom ash and utilization of stabilized bottom ash" In: *Proceedings of JSCE, 568*, 199-207.

Mitchell, J. K., and Soga, K. (2005). *Fundamentals of soil behavior*, Wiley, New York.

Mitchell, J. K., and Solymar, Z. V. (1984). "Time-dependent strength gain in freshly deposited or densified sand." *Journal of Geotechnical Engineering-ASCE*, 110(11), 1559-1576.

Nguyen, L. C., Inui, T., Katsumi, T., and Takai, A. (2011). "Effect of degradation phases of waste on compression properties in bioreactor landfills " *Proceeding of the 9th JGS Symposium on Environmental Geotechnics*, *Japanese Geotechnical Society*, 355-360.

Nguyen, L. C., Katsumi, T., Inui, T., and Takai, A. (2012). "Effect of biodegradation on mechanical properties of municipal solid waste in bioreactor landfill " *Proceeding of the 3rd Global Waste Management Symposium, Arizona, USA.*

Nguyen, T. Y. (2004). "Bio-waste reuse program: the contribution of a positioning campaign: the case of Hanoi, Vietnam. ," Master thesis, Wageningen University.

Parkin, G., and Owen, W. F. (1986). "Fundamentals of anaerobic digestion of wastewater sludges." *Journal of Environmental Engineering* 112(5), 867-920.

Plata, H. (2009). "Assessment of the mobility of heavy metals in MSWIA coastal landfill sites," PhD thesis, Kyoto University, Kyoto.

Rad, N. S., and Clough, G. W. (1984). "New procedure for saturating sand specimens." *Journal of Geotechnical Engineering-ASCE*, 110(9), 1205-1218.

Rajasekaran, G. (2005). "Sulphate attack and ettringite formation in the lime and cement stabilized marine clays." *Ocean Engineering*, 32(8-9), 1133-1159.

Rajasekaran, G., Murali, K., and Srinivasarashavan, R. (1997). "Effect of chlorides and sulphated on lime treated marine clays " *Soil and Foundations*, 37(2), 105-115.

Reddy, K. R., and Bogner, J. E. (2003). "Bioreactor landfill engineering for accelerated stabilization of municipal solid waste." In: *Invited Theme Paper on Solid Waste Disposal*, *International e-Conference on Modern Trends in Foundation Engineering: Geotechnical Challenges and Solutions*, , Indian Institute of Technology, 22.

Reddy, K. R., H. Hettiarachchi, J. Gangathulasi, N. Parakalla, J. Bogner, and Lagier, T. (2009a). "Geotechnical properties of landfilled municipal solid waste under short-term leachate recirculation operations." *Waste Management and Research*, 27(6), 578–587.

Reddy, K. R., Hettiarachchi, H., J. Gangathulasi, Bogner, J. E., and Lagier, T. (2009b). "Geotechnical properties of synthetic municipal solid waste." *International Journal of Geotechnical Engineering*, 3(3), 429–438.

Reddy, K. R., Hettiarachchi, H., Parakalla, N., Gangathulasi, J., Bogner, J. E., and Lagier, T. (2009c). "Geotechnical properties of landfilled municipal solid waste under short-term leachate recirculation operations." *Waste Management and Research*, 27(6), 578–587.

Reddy, K. R., Hettiarachchi, H., Parakalla, N. S., Gangathulasi, J., and Bogner, J. E. (2009d). "Geotechnical properties of fresh municipal solid waste at Orchard Hills landfill, USA." *Waste Management*, 29(2), 952-959.

Reinhart, D. R., McCreanor, P. T., and Townsend, T. (2002). "The bioreactor landfill: Its status and future." *Waste Management & Research*, 20(2), 172-186.

Roscoe, K. H., Schofield, A. N., and Wroth, C. P. (1958). "On the yielding of soils." *Géotechnique*, 8, 22-53.

Sato, K., Matsumura, K., Yoshida, N., Shimaoka, T., and Miyawaki, K. (2001). "Effect of environmental ground on the mechanical properties of municipal solid ash " In: *4th Symposium on Environmental Geotechnical Engineering*, 55-58.

Schmertmann, J. H. (1991). "The mechanical aging of soils." *Journal of Geotechnical Engineering-ASCE*, 117(9), 1288-1330.

Seo, S., Aramaki, T., Hwang, Y. W., and Hanaki, K. (2004). "Environmental impact of solid waste treatment methods in Korea." *Journal of Environmental Engineering-ASCE*, 130(1), 81-89.

Shimaoka, T., Zhang, R., and Watanabe, K. (2007). "Alterations of municipal solid waste incineration residues in a landfill." *Waste Management*, 27(10), 1444-1451.

Simoni, A., and Houlsby, G. T. (2006). "The direct shear strength and dilatancy of sand-gravel mixtures." *Geotechnical and Geological Engineering*, 24(3), 523-549.

Singh, D. N., and Kolay, P. K. (2002). "Simulation of ash-water interaction and its influence on ash characteristics." *Progress in Energy and Combustion Science*, 28(3), 267-299.

Sowers, G. F. (1973). "Settlement of waste disposal fills." *Proc., 8th Int. Conf. on Soil Mechanics and Foundation Engineering*.

Tanaka, N., Tojo, Y., and Matsuto, T. (2005). "Past, present, and future of MSW landfills in Japan." *Journal Mater Cycles Waste Management*, 7, 104–111.

Tatsuoka, F., Di Benedetto, H., Enomoto, T., Kawabe, S., and Kongkitkul, W. (2008). "Various viscosity types of geomaterial in shear and their mathematical expression." *Soils and Foundations*, 48(1), 155-174.

Towhata, I., Imai, Y., and Uno, M. (2010a). "Improvement of MSW subsoil for mechanical stabilization and urban use." In: *Use 6th International Congress on Environmental Geotechnics*, Delhi, 318-327.

Towhata, I., Uno, M., Kawano, Y., Kameda, M., Kita, Y., Yonai, Y., and Koelsh, F. (2010b). "Laboratory test on mechanical properties of municipal solid waste " *Doboku Gakkai Ronbunshuu C*, 66(3), 631-644.

Townsend, T., Tolaymat, T., Solo-Gabriele, H., Dubey, B., Stook, K., and Wadanambi, L. (2004). "Leaching of CCA-treated wood: implications for waste disposal." *J. Hazard. Mater.*, 114(1-3), 75-91.

Valencia, R., van der Zon, W., Woelders, H., Lubberding, H. J., and Gijzen, H. J. (2009). "The effect of hydraulic conditions on waste stabilisation in bioreactor landfill simulators." *Bioresource Technology*, 100(5), 1754-1761.

Vallejo, L. E. (2001). "Interpretation of the limits in shear strength in binary granular mixtures." *Canadian Geotechnical Journal*, 38(5), 1097-1104.

Vilar, O., and Carvalho, M. (2004). "Mechanical properties of municipal solid waste." *ASTM Journal of Testing and Evaluation* 32(6), 1–12.

Wall, D. K., and Zeiss, C. (1995). "Municipal landfill biodegradation and settlement." *J. Environ. Eng.*, 121(3), 214–224.

Wei, Y. M., Shimaoka, T., Saffarzadeh, A., and Takahashi, F. (2011). "Mineralogical characterization of municipal solid waste incineration bottom ash with an emphasis on heavy metal-bearing phases." *J. Hazard. Mater.*, 187(1-3), 534-543.

Yagiz, S. (2001). "Brief note on the influence of shape and percentage of gravel on the shear strength of sand and gravel mixture." *Bulletin of Engineering Geology and the Environment*, 60(4), 321-323.

Zekkos, D. P. (2005). "Evaluation of static and dynamic properties of municipal solid waste." *PhD. Thesis, University of California, Berkeley*.

Appendix A: Large triaxial test machine

This apparatus can be used to conduct soil mechanics experiments in order to investigate the geotechnical properties of geomaterials employed for slope stability and foundation bearing capacity.

- **Overview:**

This apparatus is used to determine the mechanical properties of a cylindrical soil specimen by performing a standard Triaxial test at a constant strain rate and measuring stress, strain, pore pressure and volume changes. To obtain various soil parameters. The following tests can be conducted:

(1) Standard Triaxial compression tests: Unconsolidated undrained Triaxial compression test, UU (JGS 0521), Consolidated Undrained Triaxial compression test, CU (JGS 0522), Consolidated Undrained Triaxial compression test with pore water pressure measurements, CU (JGS 0523), Consolidated Drained triaxial compression test, CD (JGS 0524).

(2) Special Testing Feature

While conducting triaxial compression tests, it is possible to incorporate loading or unloading at any designated stress or strain level, in the strain-controlled or stress-controlled way.

- **Testing Apparatus:**

a. Triaxial cell: (2 sets)

1. Standard specimen diameter 50mm x height 100mm 1 set
2. Large specimen diameter 150mm x height 300mm 1 set

b. Axial loading machine (DD Motor) (1 set)

c. Pressure increasing equipment (1 set)

d. Double tube burette, water tank for saturation or cell water (1 set)

e. Sensors (1 set)

f. Experiment control and data logging equipment (Computer & TC-32K) (1 set)

g. Test control software (MFT) (1 set)

h. Others accessories (1 set)

- **Functional specifications and performance:**

1) Loading machine and drive unit

Loading range: capacity 100 kN, Stroke 100 mm, Speed 0.00005~5mm/min

2) Loading frame (Reaction frame) (Geo-Research Institute made)

Capacity: 200kN, loading space 330 mm x 500 mm x 900 mm (Ht.)

3) Triaxial cell:

i) Specimen: φ 50 mm x h 100 mm)

ii) Specimen: φ 150 mm x h 300 mm)

- **Test Control/Computer Software:**

Triaxial compression testing software, MFT is pre-installed in the computer. Besides controlling the outputs to the DD Motor and EP regulators for CP and BP, it can also acquire data from the TC-32K Data Logger at any specified interval.

Fig. A.1 Complete testing system

Fig. A.2 Measurement and control parts

- **Large Triaxial Cell**

Fig. A.3 Large triaxial cell (15x30cm)

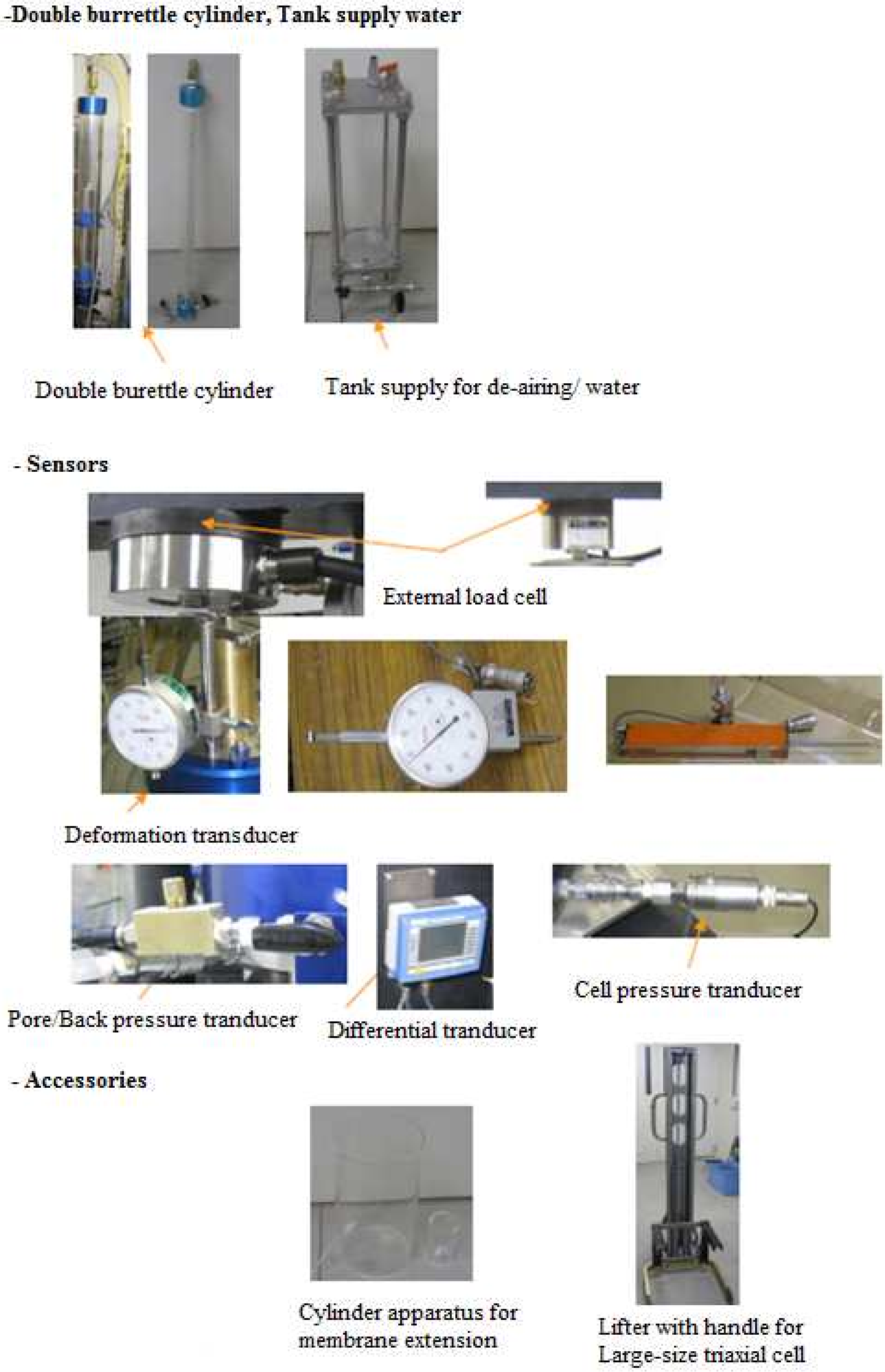


Fig. A.4 Other accessories in triaxial test

Appendix B: Lab-scale bioreactor landfill

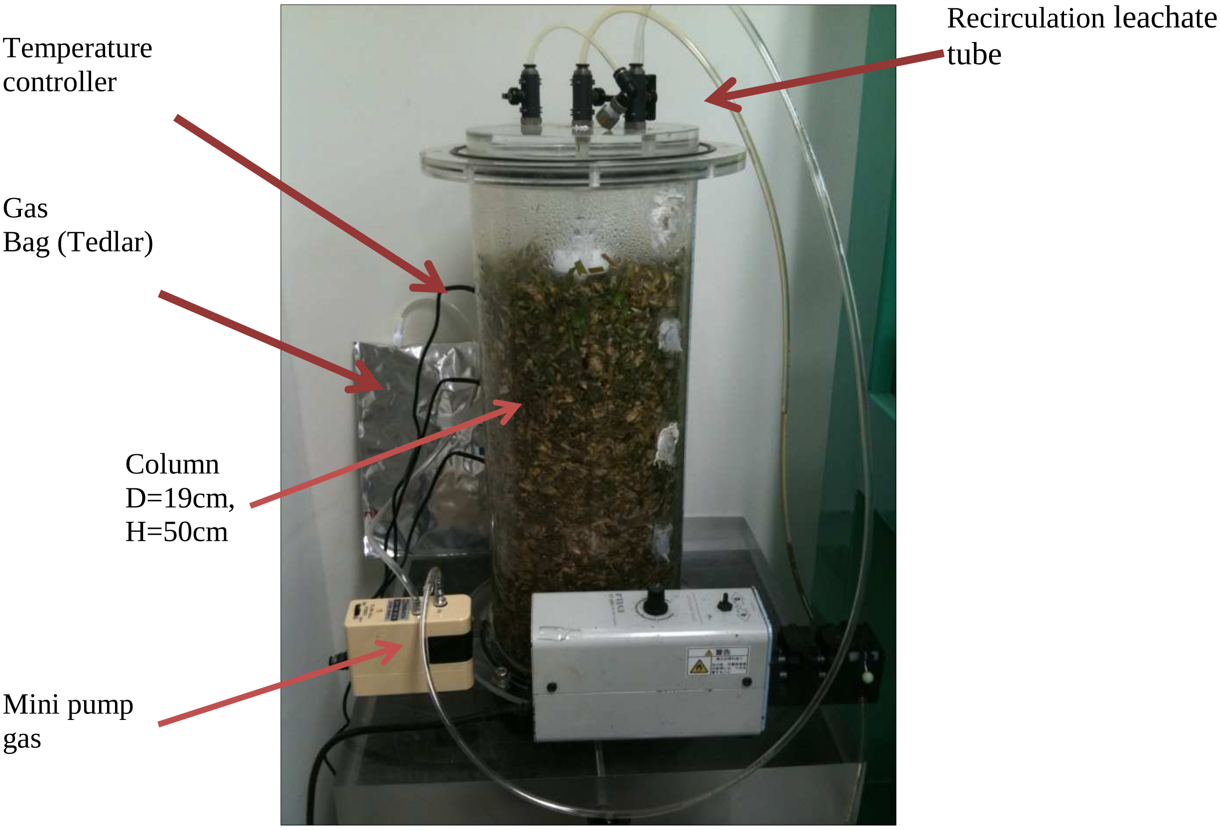


Fig. B.1 Experimental set-up for lab-scale bioreactor landfill used in this study